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Ambient pressure effects on gas metal-arc welding of mild steel

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AMBIENT PRESSURE EFFECTS ON GAS METAL-ARC

WELDING OF MILD STEEL

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Abstract

The present work was a process study to see what effects of ambient pressure variations, particularly pressure increases, might be observed in gas metal-arc welding of mild steel. Standard gas metal-arc welding equipment was mounted within a pressure vessel. The melt-off rate and stickout (distance between contact tip and arc, 1/2 in., 12.7mm) were held constant for welds made for each experimental arc length. Welds were made with 3/16, 4/16 and 5/16 in. (4.8, 6.4, 7.9mm) arc lengths and ambient pressures of 1, 2, 3, 5 and 9 atmospheres absolute. The arc length was maintained through the use of a magnified arc image on a calibrated screen. Argon with 2% by volume oxygen was used throughout with a standard gas shielding nozzle and a flow rate of 25 scfh (21.2 standard liters/min).

As ambient pressure was increased on a 3/16 in. (4.8mm) spray arc total arc voltage increased from 28 to 39V. When the ambient pressure reached 5 atmospheres absolute the flat smooth spray transfer weld reverted to a high crowned bead, the arc became sputtery and the voltage fluctuation increased. Weld cross-section and penetration showed an increase with pressure up to 3 atmospheres and decreased when 9 atmospheres was reached.

The same behavior pattern was noted with increasing pressure on a 1/4 in. (6.4mm) arc. The change in total arc voltage was from 28.5 to 44V with a transition in transfer mode and weld bead shape occurring

at about 9 atmospheres absolute where for equivalent welding parameters (264-268A, 44V) both spray and subtransitional welds were obtained.

A 5/16 in. (7.9mm) arc length remained in spray transfer throughout but showed a decreasing rate of total voltage increase (29-46.5V) and decreasing weld cross-section and depth of penetration as 9 atmospheres absolute was reached.

For all welding conditions a fine dispersion of iron oxide particles carried by the shielding gas flow were observed. The density of such particles increased with pressure such that sometimes at 5 and 9 atmospheres absolute the projected arc image was completely obscured.

Recent papers have suggested that plasma jet forces play a dominant role in spray transfer. If these plasma jets are responsible for spray transfer, the observed pressure effects can be reconciled with the theory of plasma jet formation.

As ambient pressure is increased the arc is subject to increased heat loss by conduction and constricts itself to maintain a high temperature core with sufficient conductivity to carry the welding current. The plasma jet forces are directly proportional to the gradient in current density and result in higher velocities and increased penetration as observed. As ambient pressure continues to rise the arc constriction becomes so pronounced that the gradient in current density from the morphological constriction at the electrode wire to the plate is decreased and plasma jet velocities decrease. With a lessened plasma jet force aiding transfer, the transfer characteristics revert to a subspray sputtery and globular mode. The increasing amounts of fine iron oxide particles observed with a pressure rise are a product of the increasing gas conductivity causing a sublimation of iron vapors in an active gas medium.

INTRODUCTION

Gas metal-arc welding has been a widely accepted process. Its exposed arc permitted a high degree of control and its deposition characteristics could be altered for welding on thin or thick metals in all positions. Another potential use for the process is to weld at ambient pressures greater than atmospheric. Such situations would be faced when fabricating or repairing undersea structures.[1,2]

This thesis program undertook to investigate the process at varying pressures, from a practical welding viewpoint, to see if it was adaptable to high pressure welding. Preliminary work had already been done[3-5] to evaluate the effects of ambient pressure variations on the gas metal-arc welding of aluminum. More recently the gas tungsten-arc process was evaluated at increased pressures on the welding of beryllium, aluminum and titanium.[6] Beneficial effects were observed in reducing weld porosity and increasing penetration. In this project, mild steel welding was investigated. The process exhibits different characteristics when welding steel than the lighter metals previously studied, and the potential application to steel might be quite significant if the process proved adaptable.

THEORY OF PROGRAM

The arc and the welding arc in particular has been the subject of considerable study for many years.[7-9] Nonetheless a generally accepted view of the mechanisms acting in the arc and in the transfer of metals through the arc has not yet been established. Recently several studies have been made of arc and transfer characteristics of gas metal-arc welding. These theories of arc behavior still are incomplete but general trends are evident even if the actual mechanisms are not fully clear. The reader is referred to the original papers for a full discussion of this subject as only those considerations which apply to the present study will be discussed herein.

Because even the very detailed and precise studies above did not yield an adequate description of the gas-metal-arc, the present study has not attempted to approach this process study with the same rigor. Rather a general survey of the pressure effects on gas metal-arc welding of steel was undertaken to reveal those significant and obvious characteristics of the process which might be evidenced. The results thus obtained might then be reviewed in light of current theory and further more precise studies planned.

The welding arc expends energy in causing the current to flow through a small diameter electrode, to release current carriers from the cathode, to force them across a positive plasma column, which has to be kept conducting, and into the anode. These reactions all generate heat and consume power. Additional energy is lost to the atmosphere by radiation, convection and conduction. Power losses in other conducting elements of the welding circuit are minor.

An arc welding study must focus itself on the major contributions to arc power absorption. The welding circuit is such that the same current flows through all elements. This makes it possible to measure the voltage consumed in any region as a measure of the power consumed. These distinct voltages are (Fig. 1); IR drop in the electrode stick-out, anode voltage, positive column voltage and cathode voltage. These distinct voltages must be considered[9,15,20,24] since total arc voltage will be divided differently among these regions depending on welding conditions. This information is increasingly being recognized as a more meaningful measure of welding performance than reporting only total welding voltage or heat input.[9,15]

Because of the complex factors which affect the welding arc and transfer across it, a procedure was established whereby the variable arc factors were minimized. Intuitively it would appear that only high volume arc processes would be greatly effected by changes in ambient pressure. Resistance heating of the electrode stickout is a solid state reaction, this voltage loss could be controlled if current, electrode feed rate and length of stickout (distance between contact tube and arc) were held constant. By setting a given contact tube to work distance and wire feed speed, adjustment of the power supplied could maintain a constant arc length. The melting rate for DCRP according to Lesnewich[15] is $M_{RP} = aI + bLI^2$ where a is a constant dependent upon the anode size and material, b is a constant dependent on electrode diameter and resistivity and L is the stickout distance. The first term on the right represents the anode melting contribution and the second, resistance melting. Thus when setting a constant wire feed rate and establishing a given arc length while holding total contact tip to work distance constant, the current should likewise be fixed.

By controlling the resistance heating of the electrode it would be expected that the effects of increasing ambient welding pressure would be evidenced in changes in the positive column or at the electrodes.

These regions are gas or vapor controlled and would be expected to show pressure sensitivity.

Arc lengths of 3/16, 4/16 and 5/16 inch (4.8, 6.4 and 7.9 mm) and ambient pressures of 1, 2, 3, 5 and 9 atmospheres absolute were studied.

As is well known for the gas metal-arc welding process, there are different modes of metal transfer which are responsive to a balance of arc forces. Analyses of the transfer process in gas metal-arc welding have suggested different means by which these force balances occur.[3,5,9,14-25] While welding at increasing pressures it was thought desirable to weld at a wire feed and current which would maintain the arc in one transfer mode, spray transfer.[15] Preliminary determinations of the transition current for a 1/4 inch (6.4 mm) arc at ambient pressures of 1-9 atm abs were made and the test wire feed rate was chosen to remain above transition in the spray transfer mode.

DESCRIPTION OF EQUIPMENT

Standard gas metal-arc welding equipment was modified where necessary to be mounted within a pressure vessel made from a 12 inch (30 cm) pipe tee. This vessel was provided with bolted flange openings as shown in Fig. 2. Viewing ports 6 inch (15 cm) in diameter were provided within the full end flange and in the extension in front of the arc to allow simultaneous arc observation from two directions. This vessel was built for vacuum and positive pressure capability up to 300 psig (21 Kg/cm^2 gage). In this project the fittings used limited the pressure to 120 psig (8.4 Kg/cm^2 gage).

The gas metal-arc barrel assembly, feed rolls and electrode wire reel were attached to a common carrier plate within the vessel (Fig.2). This assembly could be raised or lowered by cam adjustment and the inclination of the electrode could likewise be changed, both from outside the vessel. Mounted externally to the vessel was a variable speed 110 V AC motor which was capable of feeding the electrode at from 90-500 ipm (3.8-21.2 cm/sec). Gas, water and electric connections were made by flexible hoses fastened to fittings in the vessel wall.

A work travel mechanism was fastened to the full end flange and was driven by a drive screw running through a nut fastened to the aluminum work table (Fig. 2). A variable speed 110 V AC motor outside the vessel was capable of providing work travel speeds of 9-55 ipm (0.38-2.33 cm/sec). An adjustable mechanical pulley device was attached to the travel drive shaft outside the vessel to actuate a limit switch which terminated the weld in progress.

A rotary vacuum pump was used to evacuate the vessel. Vacuum pressure was measured with a Zimmerli gage to the nearest 0.1 mm Hg.

Two welding power sources were used during the course of this project. One was a constant potential machine and the other a drooping voltage power source. The constant potential power source was used in early low pressure work but the drooping power source was used at all pressures in later work since it provided the requisite open circuit voltage needed for the higher pressure welds.[12]

Shielding gas flow was measured with a tapered tube flowrater meter. Inlet pressure to the flowmeter was maintained constant by installation of a regulator ahead of the flowmeter.

A telescope and screen were used to view and measure the arc image. The telescope was centered on the plate surface and adjusted to project an image 16X actual size. The screen was covered with graph paper with a grid of 8 x 8 to 1/2 inch (1.27 cm). Accentuated lines on the graph paper screen 1 inch (25.4 mm) apart corresponded to 1/16 inch (1.59 mm) at the arc.

A Honeywell Electronik 19 two pen recorder was used to make simultaneous recording traces of welding voltage and current. Connections were made at the electrical leads to the vessel to eliminate any losses other than the negligible ones in the electrode holder and ground circuit.[15]

PROCEDURE

All welds other than those at 1 atm abs were made within the sealed pressure vessel. Contact tip to work distance was set with the use of spacers between the vertical contact tip and the work surface by external cam adjustment. The electrode barrel assembly was positioned vertically to eliminate as far as possible any effects of electrode inclination. The position of the barrel assembly relative to the vessel centerline was fixed by an external surface reference spacing. A mild steel electrode wire of 0.045 inch (1.2 mm) was used throughout this program (see Table 1). Ground and degreased (acetone) mild steel plates 8 x 4 x 3/4 inch (20.3 x 10.2 x 1.9 cm) (see Table 1) were used in all test runs. The plates were fastened to the work table between a tapered bracket and a toggle clamp.

With the adjustments made, the vessel was sealed and evacuated to approximately 5 mm Hg before back filling to required pressure with an argon-2% oxygen mixture. Vessel pressure was measured with a bourdon gage mounted on the chamber. A standard water cooled gas nozzle was used to provide normal gas shielding flow over the arc and weld and to fill the chamber with shielding gas.

Welds made at 1 atm abs were made within the vessel but with the end flange open. In these cases the flowmeter was mounted on the gas cylinder supply regulator. At gage pressures the flowmeter was mounted on the chamber and exited to the atmosphere. Most welds were made with a shielding flow of argon-2% oxygen at 45 standard cfh (21.2 liter/min). The flowmeter was made direct reading by correcting for the gas mixture used in this program and the inlet pressure.

The vessel was brought to test pressure and stabilized with shielding gas flowing. This pressure and flow rate was maintained during welding by manual operation of an outlet valve.

Photographs were taken of the 1/4 inch (6.4 mm) arc as projected on the screen to qualitatively show the arc shape.

Since the workpiece could be observed at all times through the end flange watch glass, adjustment of the mechanical pulley device could be made at any time during set up to determine a starting and ending point of the weld. The electrical connections were made in such a manner that a master on-off switch would simultaneously start travel and wire feed motors and energize a contactor to complete the welding circuit. The micro-switch activated by the mechanical pulley device shut off all motors and opened the contactor to end the weld.

The telescope was calibrated to give a 16X arc image by direct measurement of the magnified image of a known electrode wire diameter.

During welding some plate warpage was observed causing the base line of the arc (plate surface) to wander on the screen. This was controlled by manually making minor adjustments to the telescope inclination.

The two pen recorder was separately powered by 110 V AC and was set up to record welding current and voltage. Voltage readings were direct on a 100 volt scale. Welding current was four times the recorder indication. Many rates of paper feed were possible with this instrument but most welds were made with a 6 ipm (15.2 cm/sec) paper speed.

PROCEDURE LIMITATIONS

At once certain limits on the accuracy of this approach suggest themselves. Arc length is measured by the apparent image on the screen which could be measured with good accuracy due to the optics of the arc imaging setup.[15] The limits of the arc length are difficult to determine. The arc ends on the surface of the molten metal in the crater. Due to arc forces and solidification patterns the position of the crater surface relative to the work plate surface cannot be determined.[9] At the anode a gas metal-arc on a steel electrode shows a tapered tip.[15] A determination of the exact termination of the arc core on this taper is difficult especially as the image is formed by the light of the arc and the wire end is not always clearly defined. It was attempted in this project to set the anode end of the arc half way down the axis of the tapered portion of the electrode.

Electrode feed rates and work travel speeds were both driven by 110 V AC variable speed motors. These motors show some fluctuation in speed at a given setting as the motors heat up. This was not a consideration in this project as welding setup was of such duration that the motors ran at room temperature. Random checks of the wire and travel speeds indicated that they were constant.

The shielding gas used throughout this project was nominally argon-2% oxygen by volume. Actually this gas analyses as 1.75% oxygen. This gas mixture is widely used in steel welding due to an improvement in weld surface contour.[10,11] This gas was chosen in this project because of its wide practical application. As this gas mixture is compressed its characteristics change as well as the partial pressure of oxygen. It was not expected that chemical reactions between the metal and gas would be significant in evaluating the process so no attempt was made to maintain control over the oxygen partial pressure. The shielding gas flow was used within the vessel in a normal manner to supply a fresh gas shield to the arc and surrounding weld area. Because high pressure gas flowmeters are not generally available a standard flowmeter was installed in an exit line after a regulator so that a constant standard rate of gas could be continuously fed into the vessel through the gas nozzle and out through the flowmeter. As the ambient pressure in the vessel increased this standard rate of shielding gas became more dense and flowed over the arc area at decreasing velocities. However, some runs were repeated with a four-fold increase in standard flow rate without any measurable changes in arc or weld characteristics.

Ambient pressure in the welding chamber was measured with a bourdon gage. At all gage pressures one atmosphere was assumed to be 15 psi (1.05 Kg/cm^2). Thus a pressure recorded as 9 atm abs was actually 8 atm gage or 120 psig (8.45 Kg/cm^2 gage). Although these pressures were not exactly multiples of a standard atmosphere pressure they were indicative qualitatively of the process behavior at the indicated pressure.

Arc photographs are qualitatively accurate to show the shape of the 1/4 inch (6.4 mm) arc. These photographs were taken at an angle so as not to interfere with the projection from the telescope. The photographs are distorted and any measurements would have to be made relative to the grid on the screen. The arc showed some fluctuations during a run, more at high pressures, so that the arc could not rigorously be considered one of a steady state.

RESULTS

A series of runs were made to determine the transition current and voltage to spray transfer for an 0.045 inch (1.2 mm) mild steel electrode. These values were determined for a 1/4 inch (6.4 mm) arc and a 1/2 inch (12.7 mm) stickout, or a total contact tip to work distance of 3/4 inch (19.1 mm). Table 2 and Figure 3 show the results of these tests.

A wire feed rate of 300 ipm (12.7 cm/sec) was chosen to test an arc which was initially in the spray mode of transfer. A work travel speed of 12.5 ipm (0.53 cm/sec) was chosen to maintain a ratio of electrode feed rate to travel speed of 24.

With these settings welds were made with a constant 1/2 inch (12.7 mm) stickout and 3/16, 4/16 and 5/16 inch (4.8, 6.4 and 7.9 mm) arc lengths at 1, 2, 3, 5 and 9 atm abs. The results of these tests are tabulated on Table 3. The values listed for current and voltage are typical; the measurements are of the welds illustrated in Figures 10, 11 and 12.

The variation of arc voltage with pressure is plotted in Figures 4 and 5 for different arc lengths. Linear coordinates are used in Figure 4 and a log-log plot is made in Figure 5.

Figures 6 and 7, plotted in a similar manner, show the variation of arc power with ambient pressure for different arc lengths.

Separating these data for constant pressure and variable arc length versus arc voltage results in Figure 8.

It was observed that as the ambient pressure was raised for a given arc length, the normal fan or bell shaped plasma core of the arc was constricted to decrease its cross-section. This change is arc shape did not evidence itself very much at the anode (electrode wire) but was pronounced in the inner vapor jet of the arc. These effects are illustrated in Figure 9 in photographs of 1/4 inch (6.4 mm) arc images at the five test pressures.

It was observed at all ambient welding pressures that the ground and degreased base plate surrounding the weld had a halo of bright orange powder within the blue oxide ring, and another concentric grey powder halo outside the first. These deposits were composed of very fine individual spherical particles which exhibited residual magnetism. Some of these particles were observed to be airborne in the general welding chamber at atmospheric pressure. As the ambient pressure was raised, however, the evolution of these airborne particles was drastically increased. They were seen to be entrained in the arc plasma flow and very quickly filled the entire chamber atmosphere. Their concentration in the chamber increased rapidly and in several 5 and 9 atm abs welds, the arc image was completely obscured on the screen. These particles would settle on all internal weld chamber surfaces in small individual clumps of light brown particles. The regions between piles of particles were relatively free of them. When they were gathered in greater than their settling concentration, they looked dark brown and adhered to one another due to their mutual magnetic attraction.

These particles were observed microscopically and appeared to be spherical with the smallest resolvable individual particle about 12 microns in diameter. X-ray powder patterns were run on these samples. The airborne particles were identified as Fe_3O_4 with a very small amount of alpha iron. The bright orange adherent powders show themselves to be Fe_3O_4 with some indications that Fe_2O_3 or alpha iron might be present. The adherent grey powder was Fe_3O_4.

As ambient pressure on a weld was raised, for 3/16 and 4/16 inch arcs (4.8 and 6.4 mm), a distinct change in deposit characteristic was observed. The original spray transfer reverted to a subtransitional globular mode. This change for a 3/16 inch (4.8 mm) arc occurred between 3 and 5 atm abs pressure. For the 1/4 inch (6.4 mm) arc this change was becoming clear at 9 atm abs. A trend toward this change is observed for the 5/16 inch (7.9 mm) arc where the last columns of Table 3 show a decrease in weld area and width and an arrest in depth of penetration.

Weld cross-sections of 3/16, 4/16 and 5/16 inch (4.8, 6.4 and

7.9 mm) arc welds at five test pressures are shown in Figures 10, 11 and 12. These weld sections are reproduced in Figures 13-17 where constant pressure, variable arc length welds are grouped.

Simultaneous current and voltage traces showed that as ambient pressure was raised, the arc became more unstable. Current and voltage fluctuations increased from their mean values. At 9 atm abs the 4/16 and 5/16 inch (6.4 and 7.9 mm) arcs were observed to be sputtery corresponding to occasional transfers of visible droplets. No significant spatter was encountered.

DISCUSSION OF RESULTS

Transition values for current and voltage for a 1/4 inch (6.4 mm) arc are listed in Table 2 and plotted in Figure 3. These values are typical. No shielding gas flow was used during these tests and a pressure rise was observed during adjustment to transition conditions. For this reason, the points representing these runs have been widened to show the pressure range within which transition was determined. It is interesting to note that the current and voltage at transition both rise with pressure, which has been noted in aluminum gas metal-arc welding at varying pressures.[5] The arc current functions in the arc to melt the electrode and to maintain the high temperature and thus the high conductivity of the plasma core.[15,26] As has been suggested by Salter[5] and others[25,28] increasing pressure will increase the plasma jet velocity. This will carry more heat away from the electrode and necessitate an increased current for the melting rate. As the pressure increases heat losses rise due to higher plasma flow rates. The energy needed for heating the incoming gases must express itself as an increase in voltage.[26]

Examination of Table 3 reveals immediately that the current drawn by a given arc length, melt-off rate and stickout is not constant as pressure increases. Thus the relationship as suggested by Lesnewich[15] and discussed in the theory of this program is shown not to be valid for pressure variations. At a fixed pressure for those conditions which satisfy the equation, the current density at the electrode probably does not vary. This would cause a constant or almost constant plasma jet entrainment of cold gases and a uniform cooling of the electrode. But when the ambient welding pressure is increased, as discussed above, the electrode is cooled to a greater extent and additional current is needed to maintain a given arc length and melt-off rate, thus invalidating the application of Lesnewich's relation to varying pressures.

The variation in current with increasing pressure at constant arc length, might be thought to affect the IR voltage. A simple calculation based on the maximum current variation of 24 amp for the 5/16 inch (7.9 mm) arc yields a change in IR voltage of approximately 0.29 volts. This amount is not significant in this study. This calculation was based on a mean stickout resistivity of 99.3[27] micro-ohm cm at a temperature halfway between room temperature and melting. The arc voltage figures listed can then be considered as unaffected by the current variations.

When Figures 4 and 5 are examined, it is evident that arc voltage increases with ambient pressure in a similar manner until at about 4 atm abs for a 3/16 inch (4.8 mm) arc. A divergence between 5/16 and 4/16 inch (6.4 and 7.9 mm) arcs begins to be evident at 9 atm abs.

These same changes are evident in the deposited weld as the weld changes from the characteristic wide flat spray transfer weld to a narrow and more highly crowned weld indicative of subtransitional globular transfer (see Figures 10, 11, 12). Figure 5 shows that in the range of pressures where the arc behaves in a normal spray mode, the voltage-pressure curves suggest a power relationship. Departure from this power dependence is shown for the 3/16 inch (4.8 mm) arc above 3 atm abs, and for the 4/16 and 5/16 inch (6.4 and 7.9 mm) arc above 5 atm abs.

When these data are considered on a basis of total arc power similar results are obtained (Figures 6 and 7).

Examination of the columns of Table 3 which measure the weld width along the original plate surface and depth normal to it, it is seen that at these characteristic departures in weld appearance and performance from a spray transfer mode, bead width and depth of penetration into the plate decrease. The total weld cross-section areas show the same trend but not as clearly due to a change in bead shape (Figures 10, 11, 12).

It has long been known that arc voltage would increase with pressure due to increased losses,[7,8,29] but it was not until Maecker[26] demonstrated and analysed plasma jets that their role in arc welding transfer mechanisms became clear. Theories of arc transfer now include plasma forces and electromagnetic forces to account for transition currents.[3,5,14,16-19,21,22,25,26,28,30,31] These plasma forces are shown in several of these studies to be the dominant metal transfer forces in the spray mode. The results of this study seem to show that it is the effects of ambient pressure on these plasma jets which change the arc characteristics.

In analysing magnetic field strength in an arc, Maecker[26] showed a higher radial pressure exists at points of constriction and that a tendency toward pressure equalization will cause a flow along the axis toward larger cross-sections and lower current density. This pressure along the axis increases with current density. The initial flow leads to aspiration of cold gases from the vicinity. This cold gas flow, however, constricts the discharge cross-section at the wire electrode to increase the pumping action. This process continues until the temperature gradient becomes steeper and a steady state is reached. The current paths are drawn into the plasma jet due to its good conductivity and supply Joule heat to maintain its temperature and conductivity to offset the rapid cooling of the plasma jet by heat conduction.

As ambient pressure is raised, the thermal conductivity of a gas rises. (This equivalent to changing shielding gas.) This increased thermal conductivity will constrict the arc and lead to higher velocity plasma jets. The volume of cold gas being entrained in the plasma flow increases and requires increased current and voltage as discussed above. The constriction will cause the inner plasma jet to contract and rise in temperature due to the increased current density. The higher temperature plasma is more highly ionized and can thus conduct the welding current. The effect of gas thermal conductivity on increasing voltage has been noted in many sources.[3,5,29,32,33,34]

As the ambient welding pressure is raised, therefore, the plasma flow rate and velocity increase resulting in the increased drop transfer rate reported[3,5] and the increased penetration both reported[3-6] and observed here. But these effects do not continue in mild steel welding to greater and greater pressures. Retarding arc forces are noted.[16,19,35,36] High speed motion pictures have shown[19] that the moment of entry of the drop into the weld pool was preceded by a region which in most cases is characterized by a sharp decrease in velocity. This decrease in velocity was attributed to the increasing effect of the vapor jet from the workpiece or with the action of the arc stream which is reflected from the surface of the pool.

In the present study, ambient pressure increases would constrict the current carrying path from the electrode to the workpiece. This constriction would in the manner suggested by Maecker result in a plasma jet. In most welding conditions the degree of constriction at the workpiece is negligible and the constricted electrode jet is the only one that need be considered. In high pressure welding the change in current density from the constricted electrode to the workpiece is reduced. This reduces the velocity of the jet issuing from the electrode and increases the workpiece plasma jet velocity. When these effects become pronounced, the entraining plasma force on the droplet is counteracted and the metal transfer will revert from spray to globular modes.

In a short arc length, the amount by which the current density can decrease between electrode and plate is limited. A relatively low ambient pressure might be expected to upset the balance of forces causing spray transfer. This has been noted for the 3/16 inch (4.88 mm) arc.

Longer arc lengths would be less affected by workpiece plasma jets. The force due to electrode plasma would be increased due to a greater total change in current density. Thus any change in arc transfer characteristics would not be expected until higher pressures were reached. This was as observed. The 1/4 inch (6.4 mm) arc was just at the point of transfer characteristic change at 9 atm abs. Table 3 and Figure 11 show that both crowned and flat welds were obtained at effectively the same welding conditions.

The retarding effects of such a plasma effect might also account for the decreased width, penetration and melted volume of the higher pressure welds. The detachment rate would probably decrease as the droplet volume increased. This would evidence itself as a more erratic arc, which was, in fact, observed. At those pressures where normal spray transfer is observed Figure 5 shows a uniform power relationship between pressure and voltage. Where these curves depart from linearity, Table 3 reveals decreasing width or penetration or section of weld bead.

The plasma velocity and flow rate would decrease somewhat when the arc transfer is being retarded. As discussed above, this would lessen the current required to melt the electrode. This was observed in Table 3 for those cases where transfer reverted to a subtransitional mode.

Data plotted as in Figure 8 is often used to show the length variation of a parameter and then extrapolating to zero length.[9,15] Solid lines are drawn through data points representing spray transfer. As discussed in the theory of this program, the total voltage is made up of stickout IR voltage, anode drop, plasma and cathode drop voltage. As discussed already the IR voltage drop would remain constant and would not show the minor effect of current variation. When the curves are extrapolated to zero arc length, the contribution to total voltage of the plasma voltage is eliminated. The zero arc length voltages for the different pressures increase with pressure. Since the IR stickout voltage is constant, the sum of anode and cathode voltages increase with pressure and in differing amounts as shown by the varying slopes of the constant pressure curves. Similar results are reported by Avilov in underwater welding arcs.[37] In discussing the assumptions lying behind the melting rate equation of Lesnewich,[15] mentioned in "Theory of the Program," Akulov[24] has pointed out that the electrode voltage drop would have to be independent of the temperature of the end of the electrode. Above it was noted that Lesnewich's relationship did not hold at increasing pressures because the electrode was cooled and the current increased accordingly. Here it is seen that a voltage increase might be expected in the anode region. This follows Maecker's[26] analysis of plasma jets where he says that the entrained cold gas has to flow over the electrode and be heated and accelerated. The energy needed for this should express itself as an increase in voltage at the electrode. If Maecker's analysis is valid, the anode voltage drop would increase with pressure as more energy is needed with increasing plasma flow rates.

A voltage will also be developed in the plasma core. It is generally agreed that the plasma voltage gradient is constant so that at a given pressure, plasma voltage would be directly proportional to arc length. This gradient should increase with pressure to offset the increased arc losses. Unfortunately it was not possible to identify the partition of arc voltage into its components to see where the greatest response to pressure variation occurred. The different slopes to the voltage versus arc length curves in Figure 8 contain large (for the voltages measured) contributions from errors in measurement discussed in "Procedure Limitations." It was felt that this lack of precision did not warrant plasma voltage gradient measurements.

Figure 9 is a poor method of illustrating how the arc becomes constricted at increasing pressures. This constriction changes the plasma flow and the arc transfer characteristics.

Temperature measurements in the arc have shown that the transferring metal is between its melting and boiling temperature.[9,25,42] As the ambient pressure is increased the arc core temperature will increase to maintain a conducting path through the constricted plasma. It has been observed for some time that the transferring metal in the plasma core is composed of discrete droplets which are surrounded by a vapor shield which streams away from the electrode.[25,38,39]

As the arc column temperature rises with pressure an increasing amount of metal vapor should be liberated. The low ionization potential of this vapor serves to further constrict the arc. The amount of metal transferred as a vapor at atmospheric pressure has been variously estimated as from 1/2 to 20% of the total transfer.[9,39,40]

In normal spray transfer most of these vapors condense in the weld pool under the action of the plasma. When an entraining plasma force is absent or if the plasma flow increases as in pressurized welding more of this vapor will leave the weld zone and condense in the cooler surrounding atmosphere. This phenomena has been observed at vacuum and positive pressures, with steel or aluminum.[41-47]

When pressure on the arc is raised, an increased volume and flow rate of plasma gas will carry the additional metal vapors more forcefully toward the weld pool. But with this increased velocity of flow more turbulent reactions will occur as the plasma is deflected by the plate surface and increasing amounts of metal vapor will be carried in the gas stream out of the arc region where these vapors will immediately solidify. At higher pressures the more erratic arc will disturb the plasma flow and escape of the metal vapor might be expected to increase.

This was exactly what was observed. In fact the flow of shielding gas rebounding from the work surface was revealed by the solidified vapor particles carried with it.

The deposits of powders found on the work surface would probably be due to the particles adhering to the relatively cool plate surface.[41] In pure argon shielding these powders were analyzed to be alpha iron. The additions of oxygen to the gas atmosphere would allow the hot reactive metal vapors to oxidize. The stable oxide of iron with lowest oxygen content is Fe_3O_4. The powders were identified as Fe_3O_4 which would also account for their settling behavior.

It is interesting that the oxide powder on the plate surface nearest the weld was bright orange and the airborne powder was light brown. Magnetite is expected to be black as evidenced by the outside plate halo.[48] X-ray examination of both "wrong color" particles showed that they were not completely Fe_3O_4. It is outside the scope of this project to speculate on the oxidation reactions which might explain these observations.

CONCLUSIONS

As the ambient gas pressure is increased, gas metal-arc welding of mild steel loses many of the inherent advantages of the process. A spray arc with constant wire feed rate and arc length showed the following changes:

1. The arc was more and more obscured by clouds of fine Fe_3O_4 particles carried in the shielding flow.
2. The arc became increasingly unstable leading to a reversion to subtransitional globular transfer at sufficiently high pressures.
3. Arc voltage rose most rapidly while the arc remained in spray transfer and rose only slightly after reversion to globular transfer mode.
4. The weld bead remained flat until reversion to globular spray transfer where a highly crowned bead was formed.
5. Bead width, depth of penetration and cross-sectional area increased until spray transfer became erratic, after which they stabilized or decreased.

The observations above can be rationalized with arc transfer theory wherein plasma jets are a dominant force in drop detachment and transfer. Increased ambient pressure constricts the arc due to the greater thermal conductivity of the gas. This constriction results in higher velocity and volume of plasma jet flow. Thus more gas vapors are carried into the general atmosphere; penetration and bead width increase and voltage and current rise. Further pressure rise will begin to decrease the current density gradient and lower plasma jet forces. The arc will revert to erratic and finally to subtransitional globular transfer with highly crowned welds of reduced depth, width and cross-section.

FIGURE 1. ARC VOLTAGE DIVISION

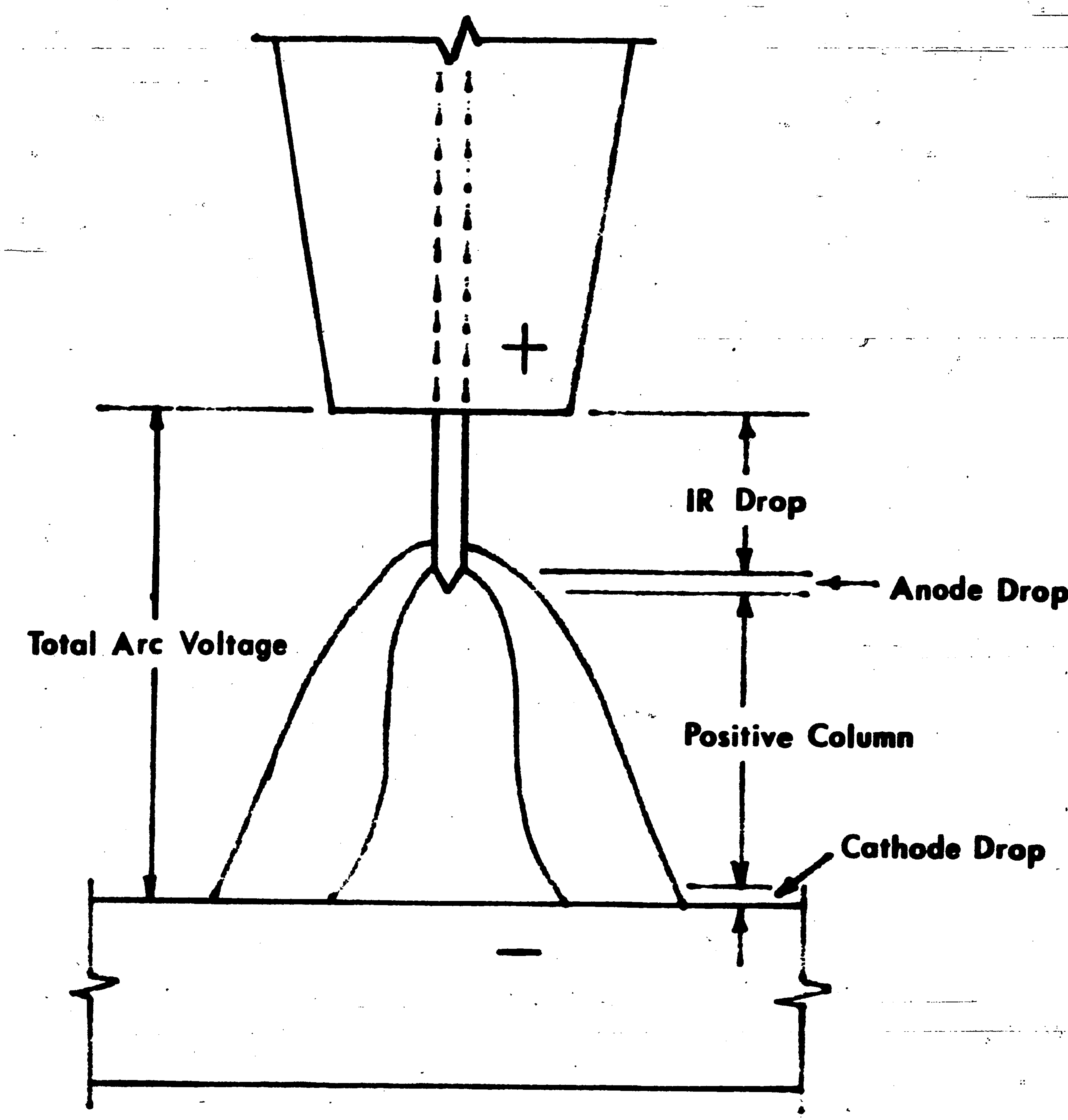


FIGURE 2. EXPERIMENTAL SETUP

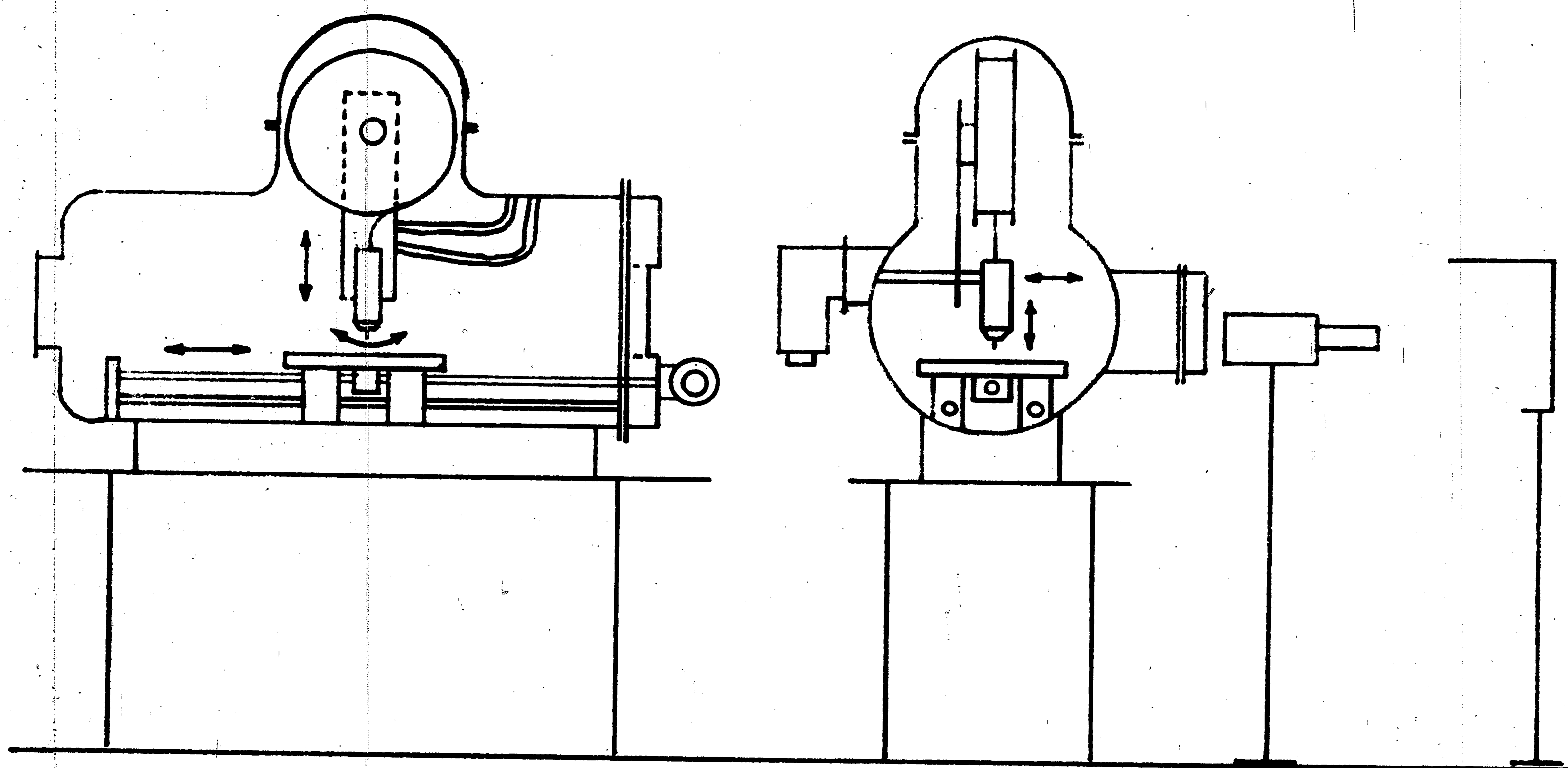


FIGURE 3. SPRAY TRANSITION WITH CHANGING PRESSURE

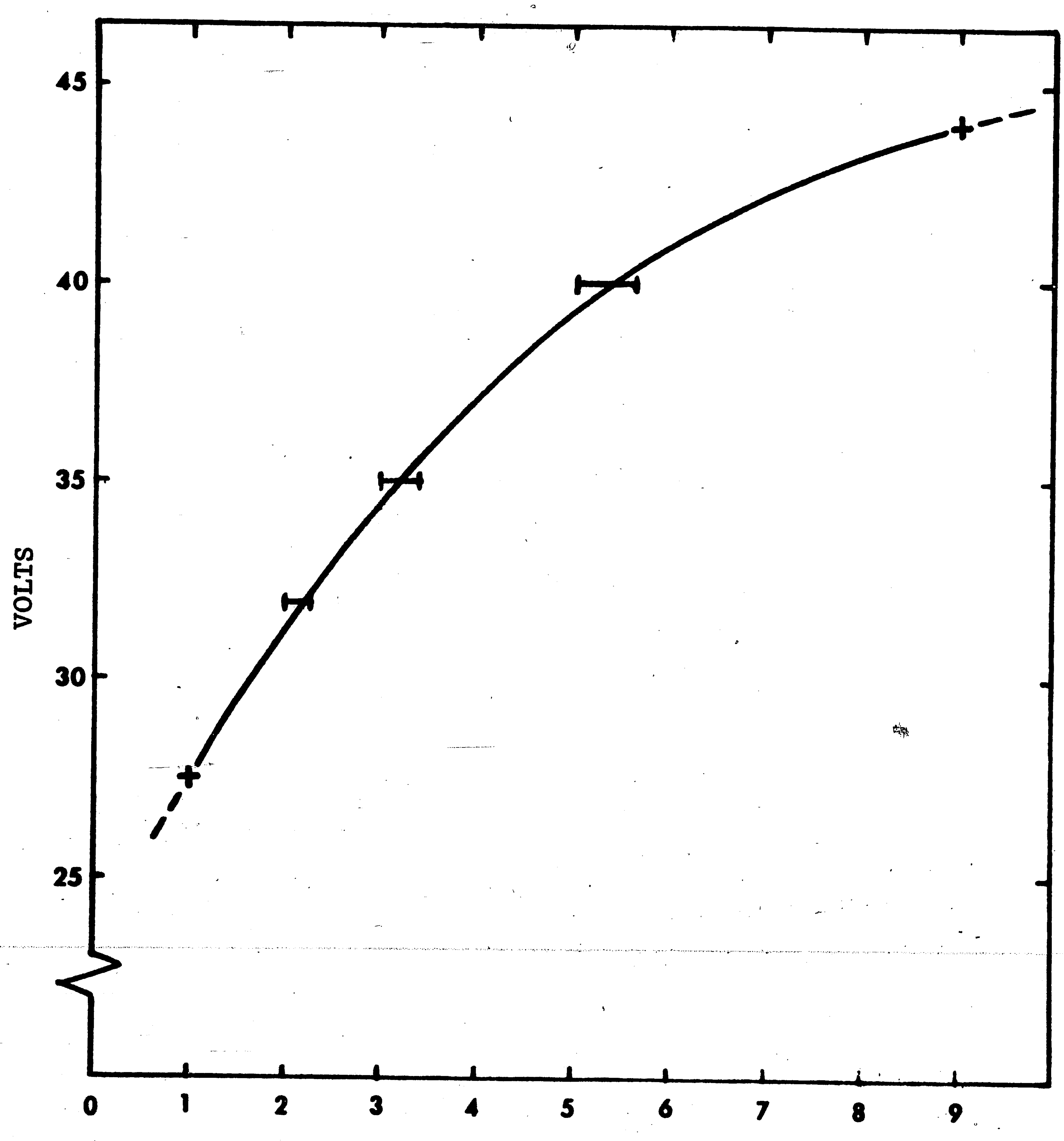


FIGURE 4. ARC VOLTAGE VS. PRESSURE (LINEAR COORDINATES)

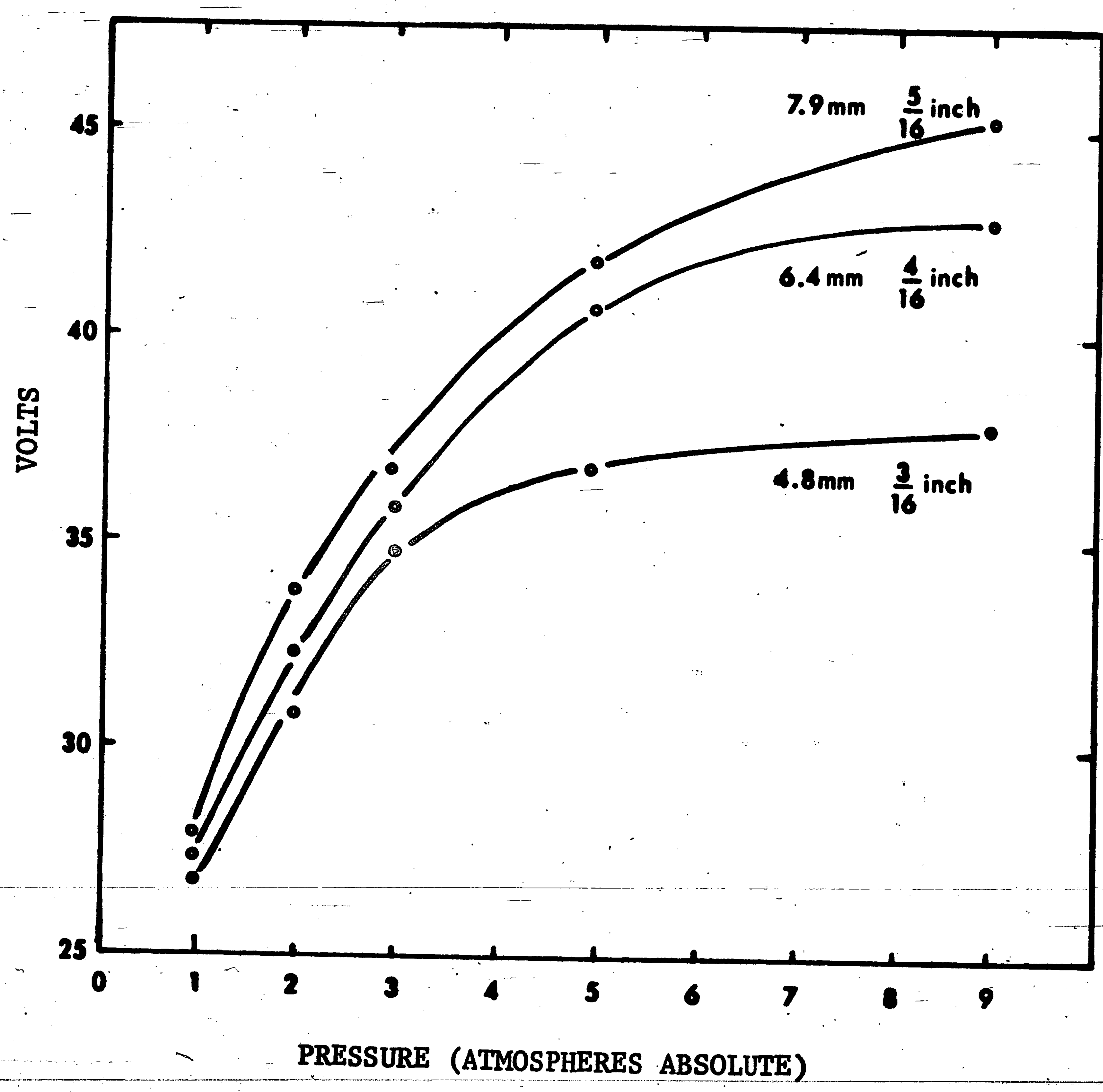


FIGURE 5. ARC VOLTAGE VS. PRESSURE (LOGARITHMIC COORDINATES)

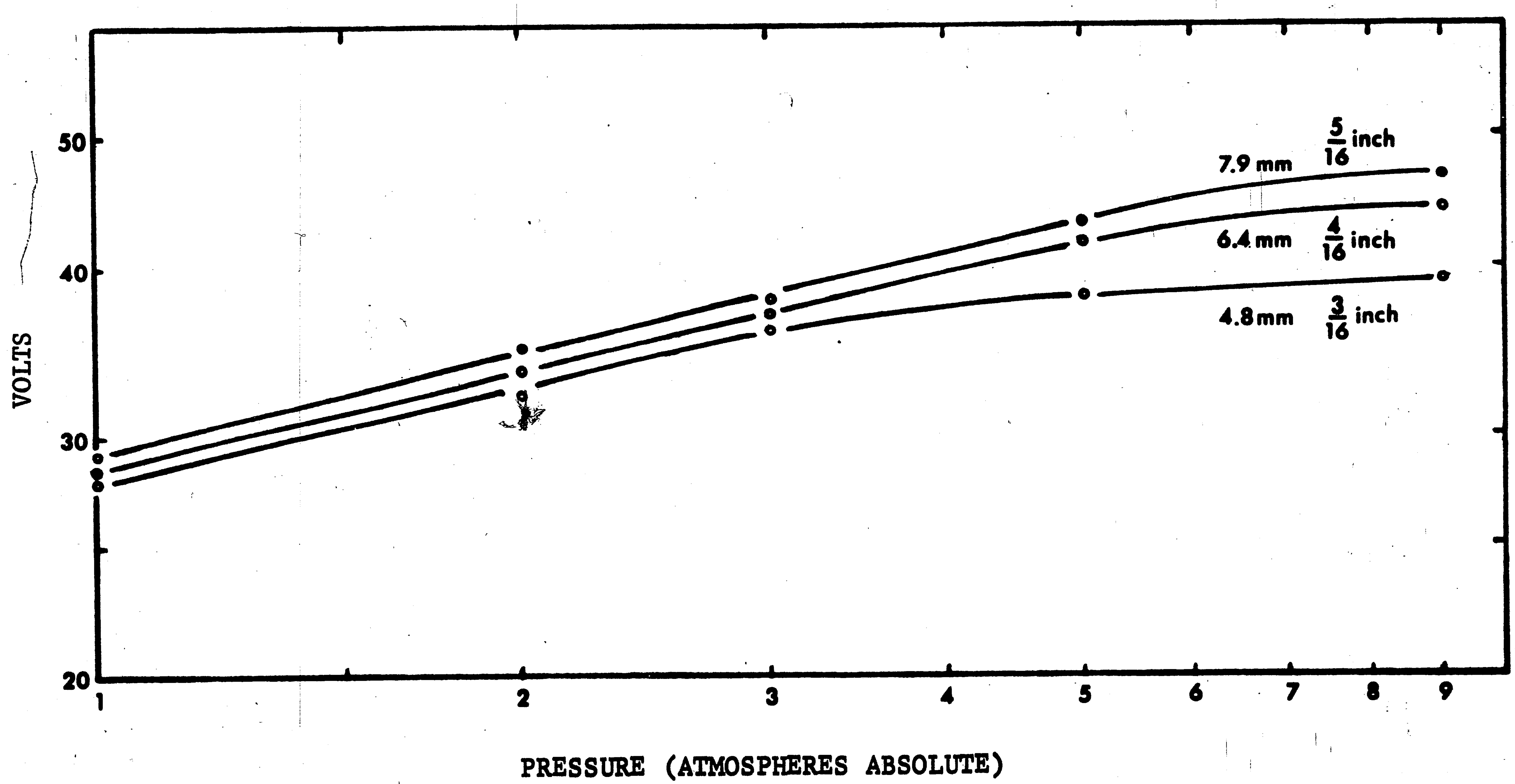


FIGURE 6. ARC POWER VS. PRESSURE (LINEAR COORDINATES)

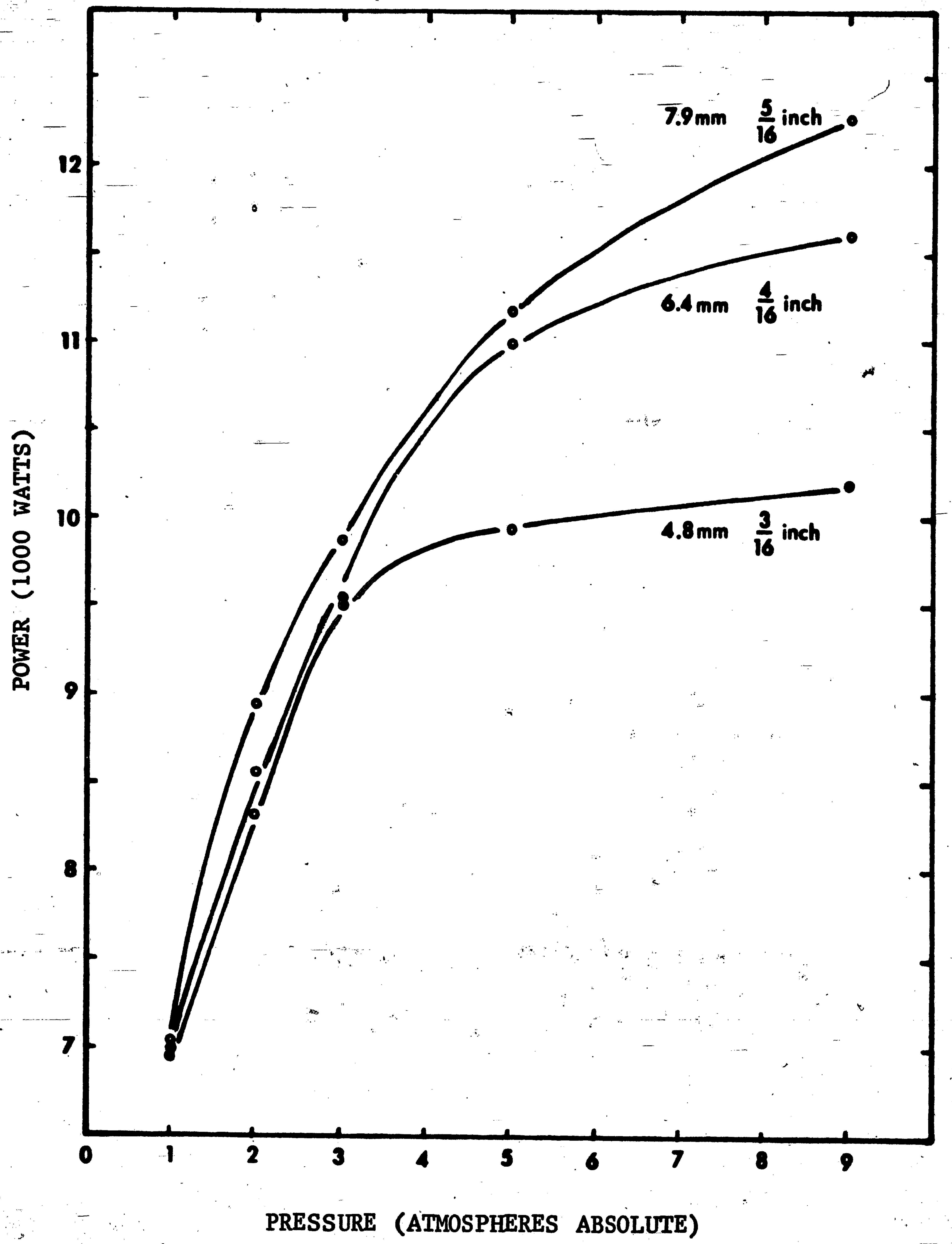


FIGURE 7. ARC POWER VS. PRESSURE (LOGARITHMIC COORDINATES)

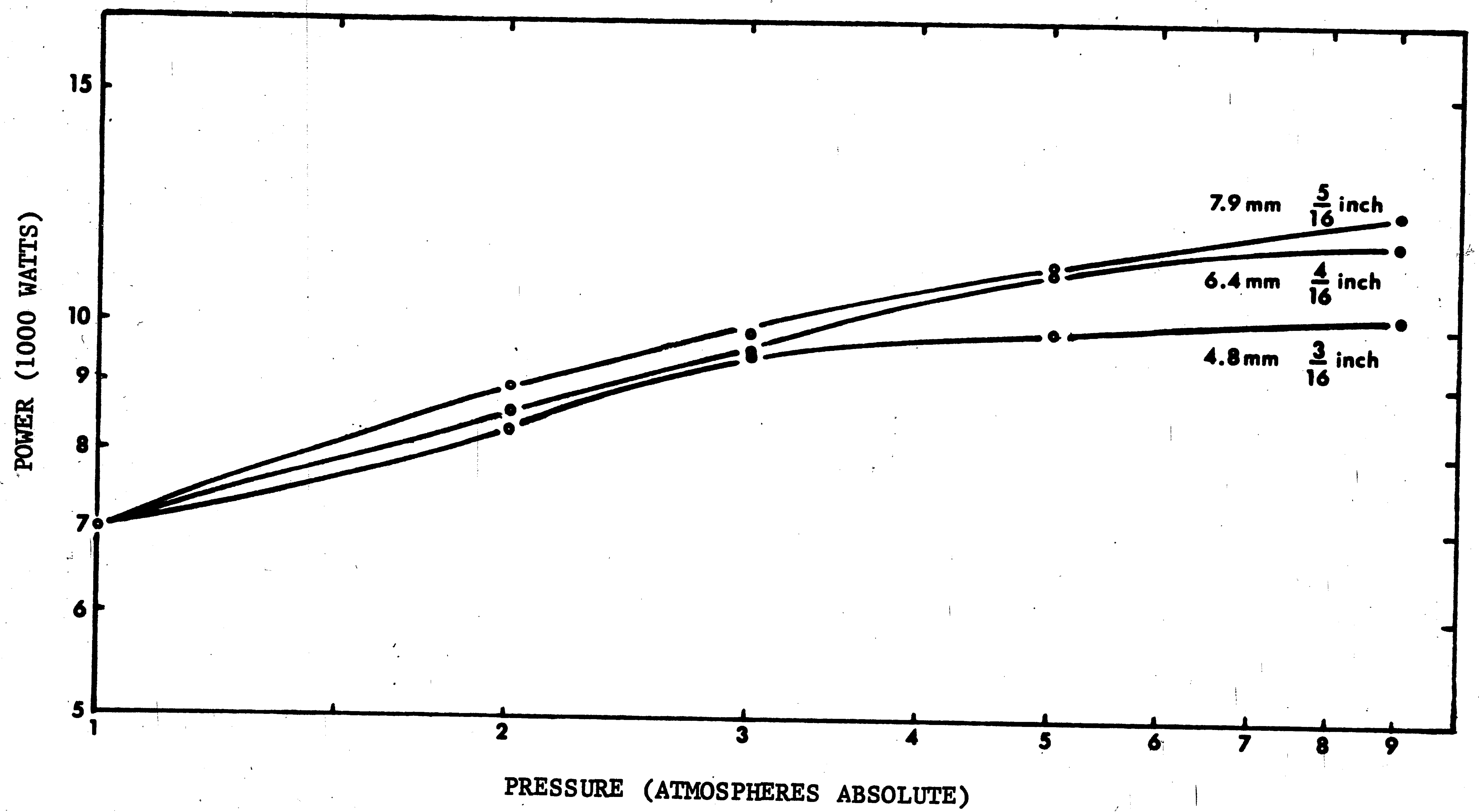
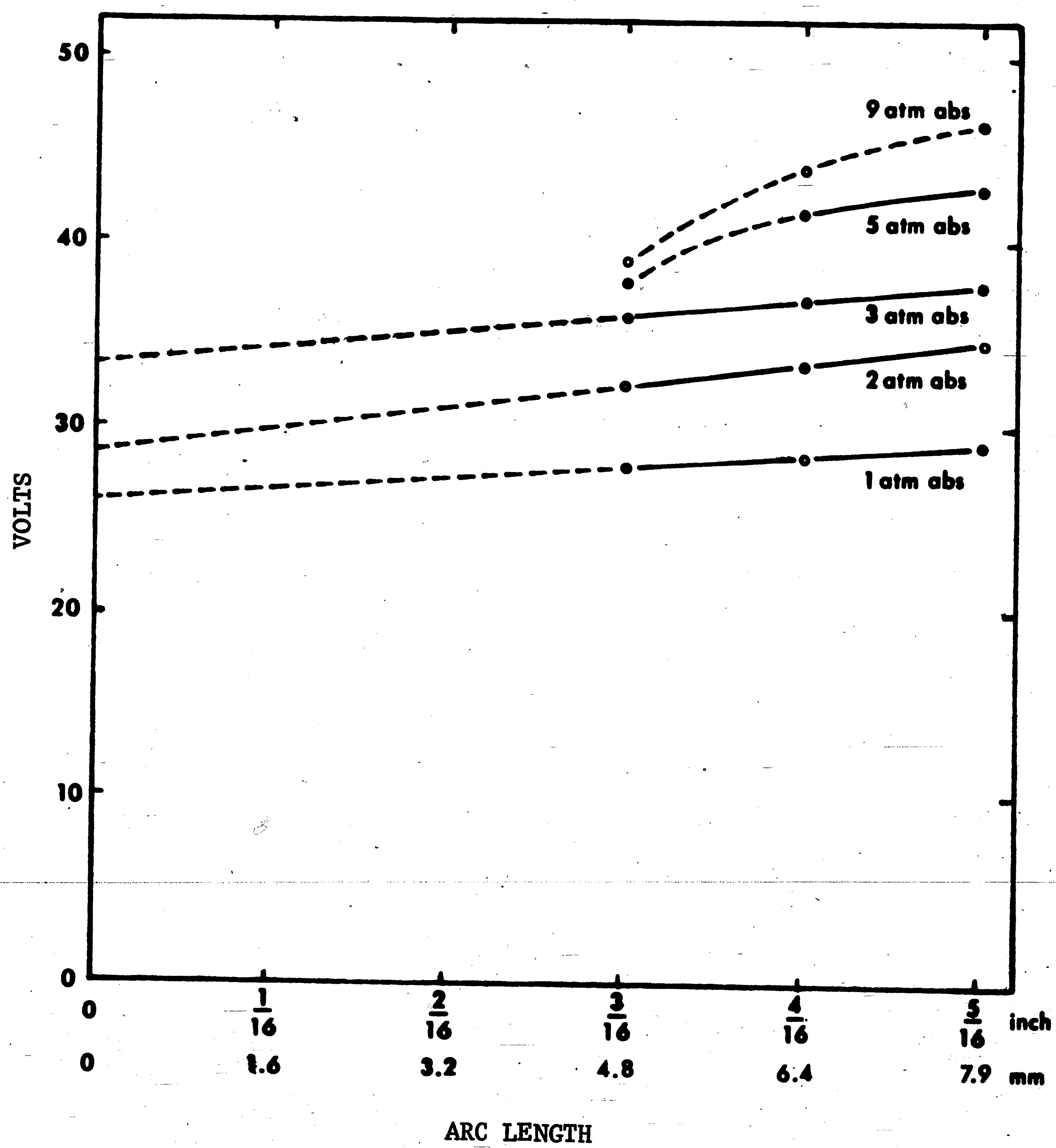


FIGURE 8. ARC LENGTH VS. VOLTAGE



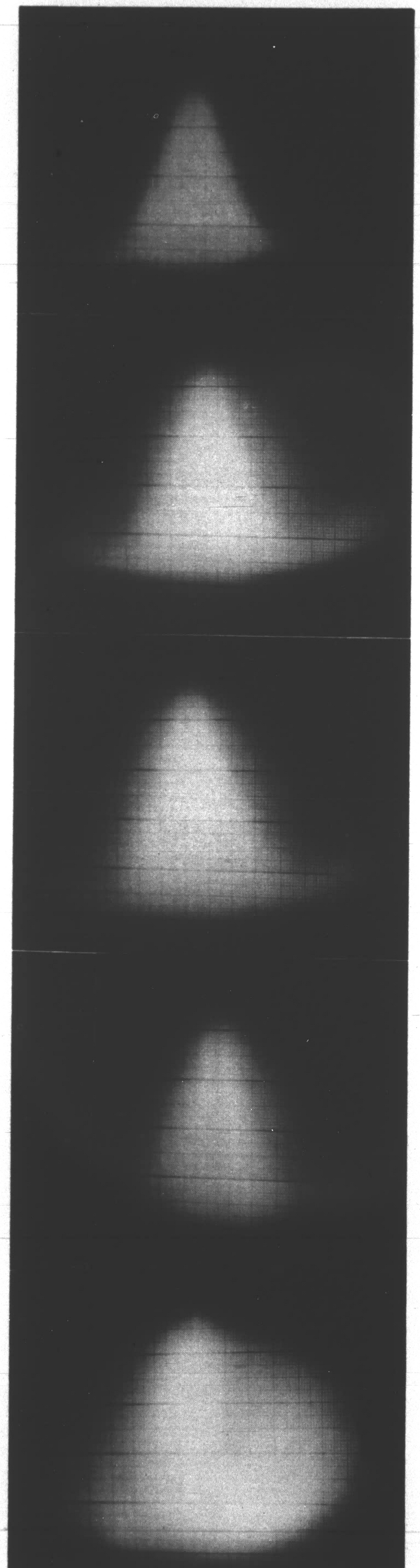


FIGURE 9. ARC SHAPE AT 5 PRESSURES

1/4 INCH (6.4mm) ARC LENGTH

1 ATMOSPHERE ABSOLUTE

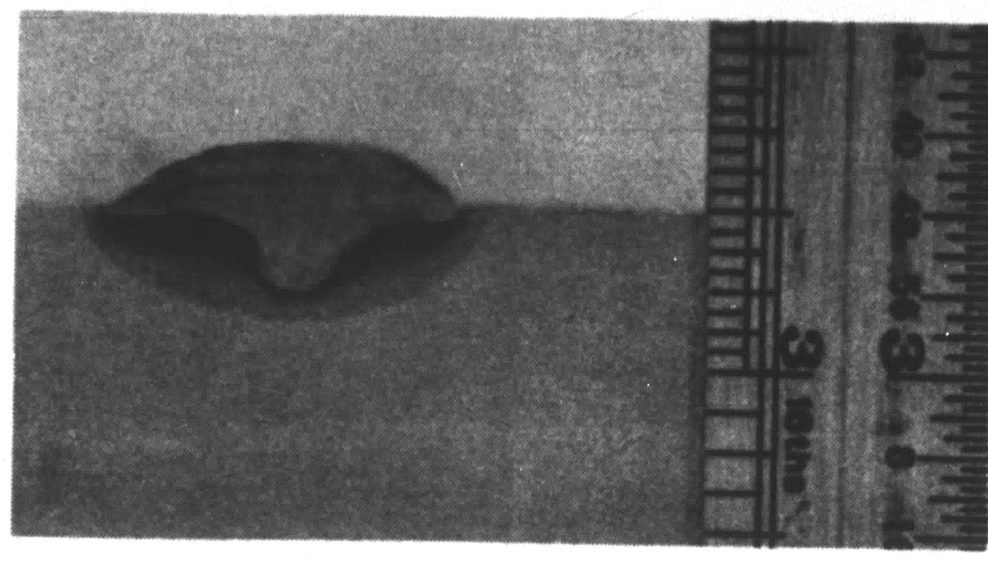
2 ATMOSPHERES ABSOLUTE

3 ATMOSPHERES ABSOLUTE

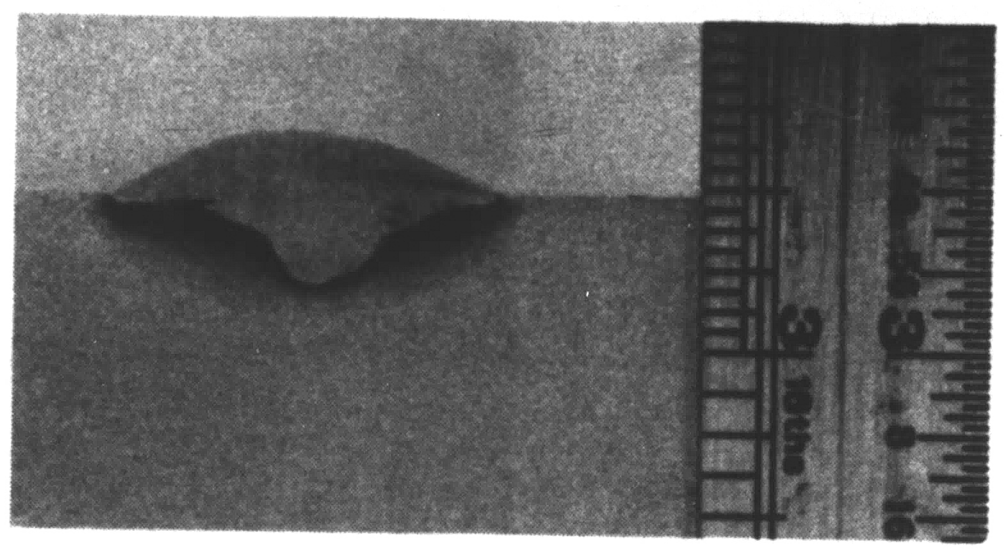
5 ATMOSPHERES ABSOLUTE

9 ATMOSPHERES ABSOLUTE

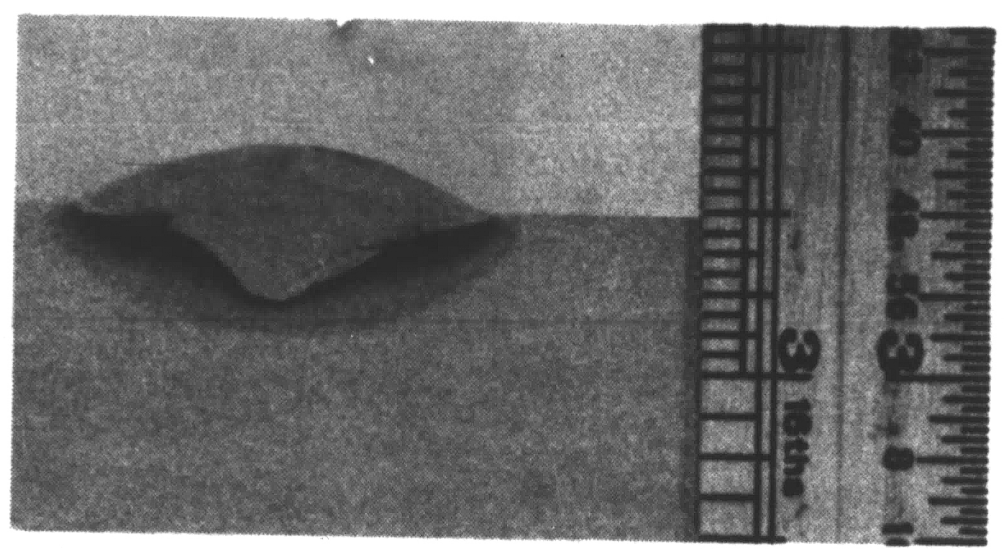
FIGURE 10. WELD CROSS-SECTIONS, 3/16 INCH (4.8mm) ARC, 5 PRESSURES



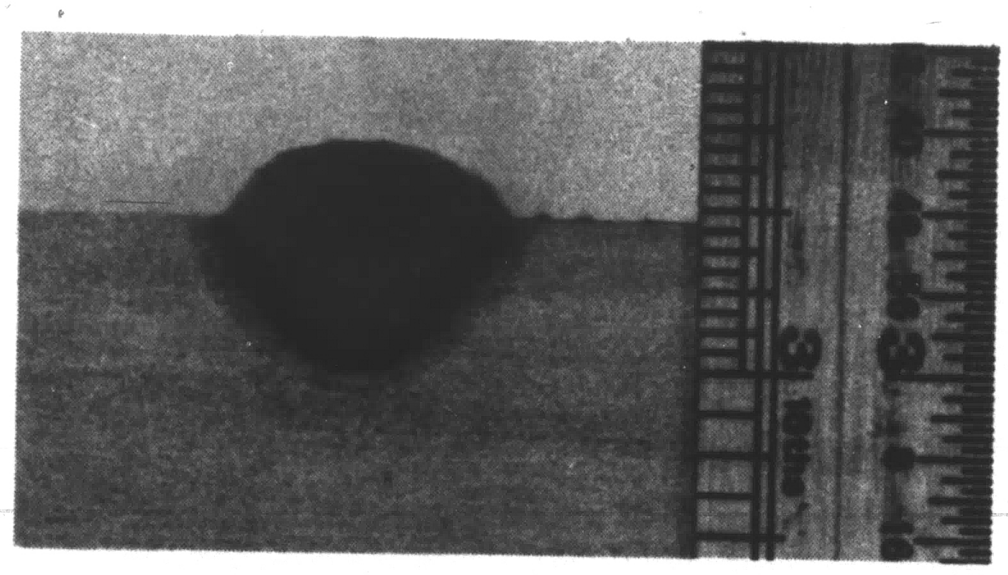
1 ATMOSPHERE ABSOLUTE



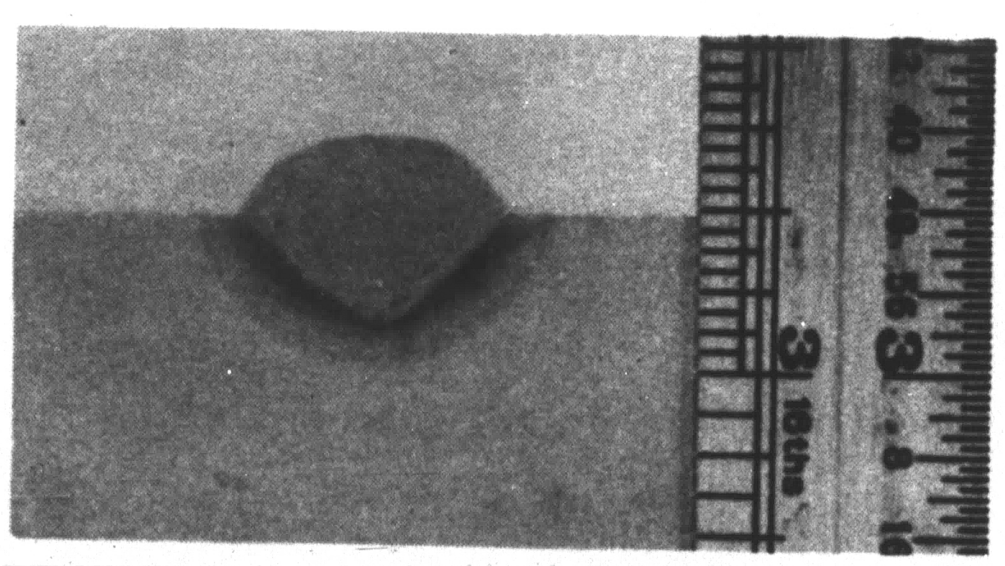
2 ATMOSPHERES ABSOLUTE



3 ATMOSPHERES ABSOLUTE

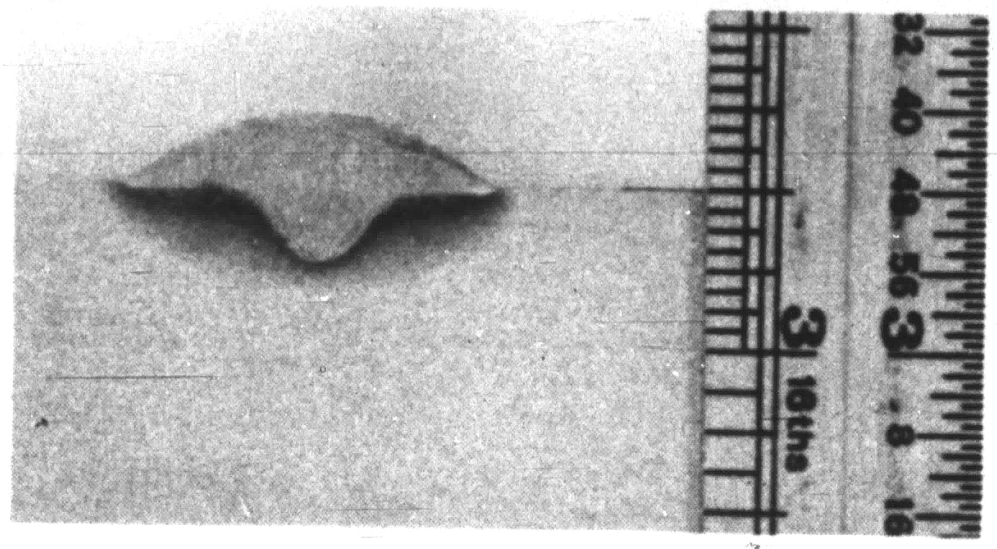


5 ATMOSPHERES ABSOLUTE

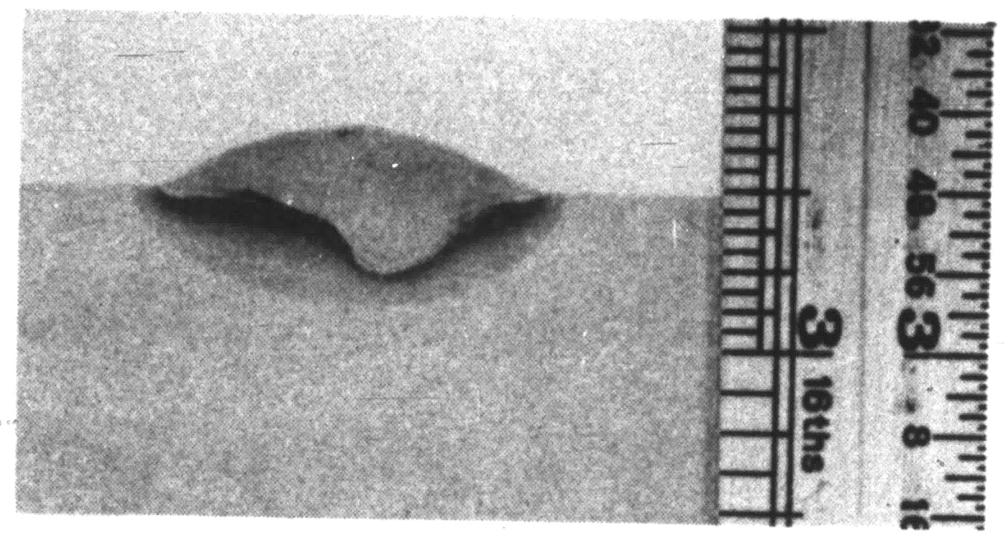


9 ATMOSPHERES ABSOLUTE

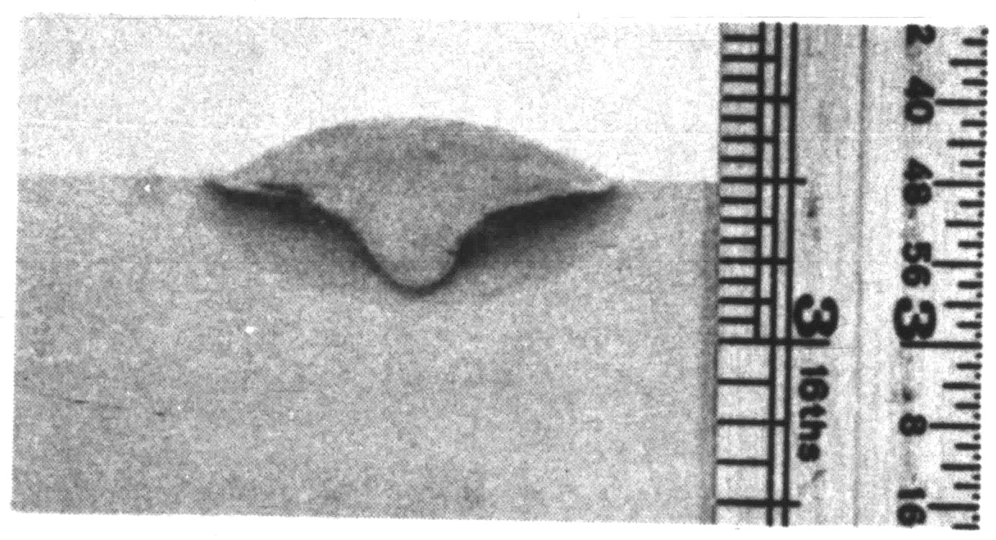
FIGURE 11. WELD CROSS-SECTIONS, 1/4 INCH (6.4mm) ARC, 5 PRESSURES



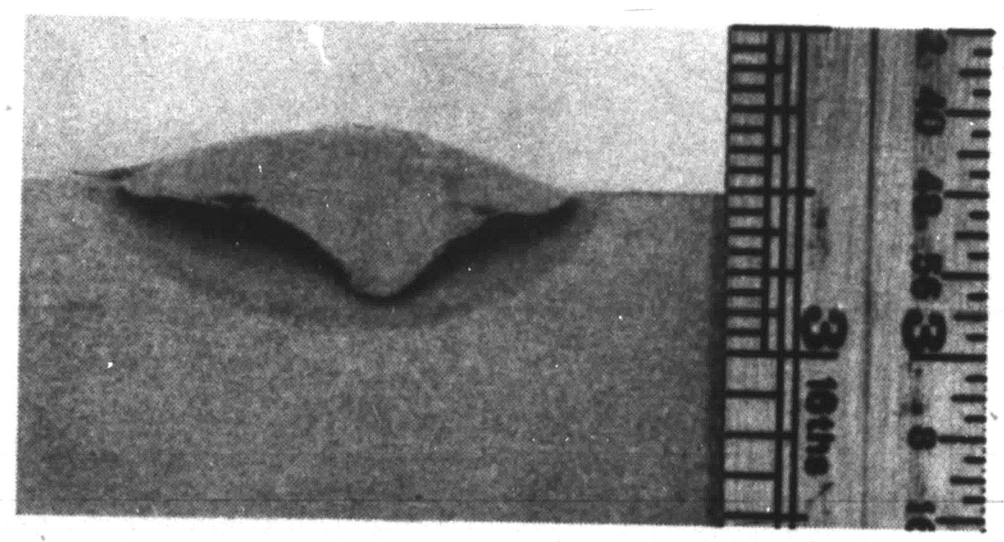
1 ATMOSPHERE ABSOLUTE



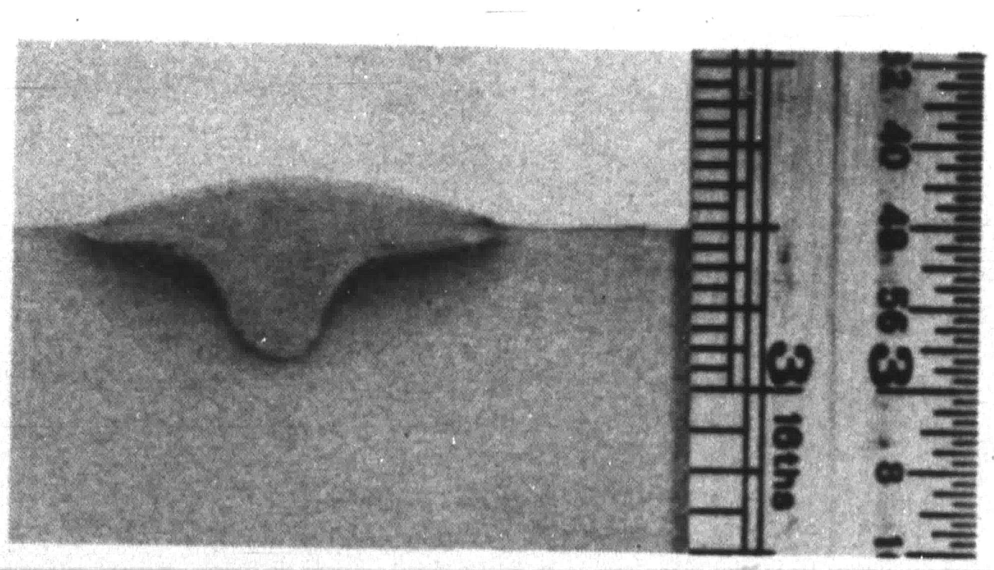
2 ATMOSPHERES ABSOLUTE



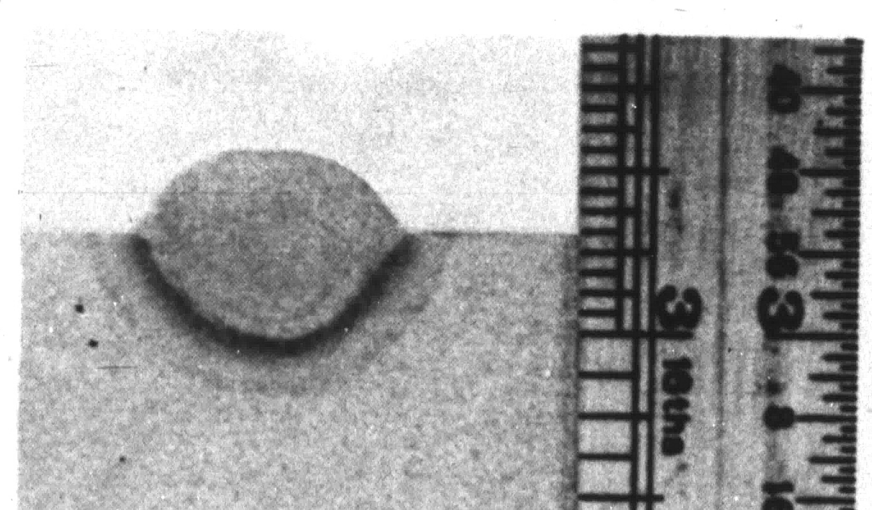
3 ATMOSPHERES ABSOLUTE



5 ATMOSPHERES ABSOLUTE

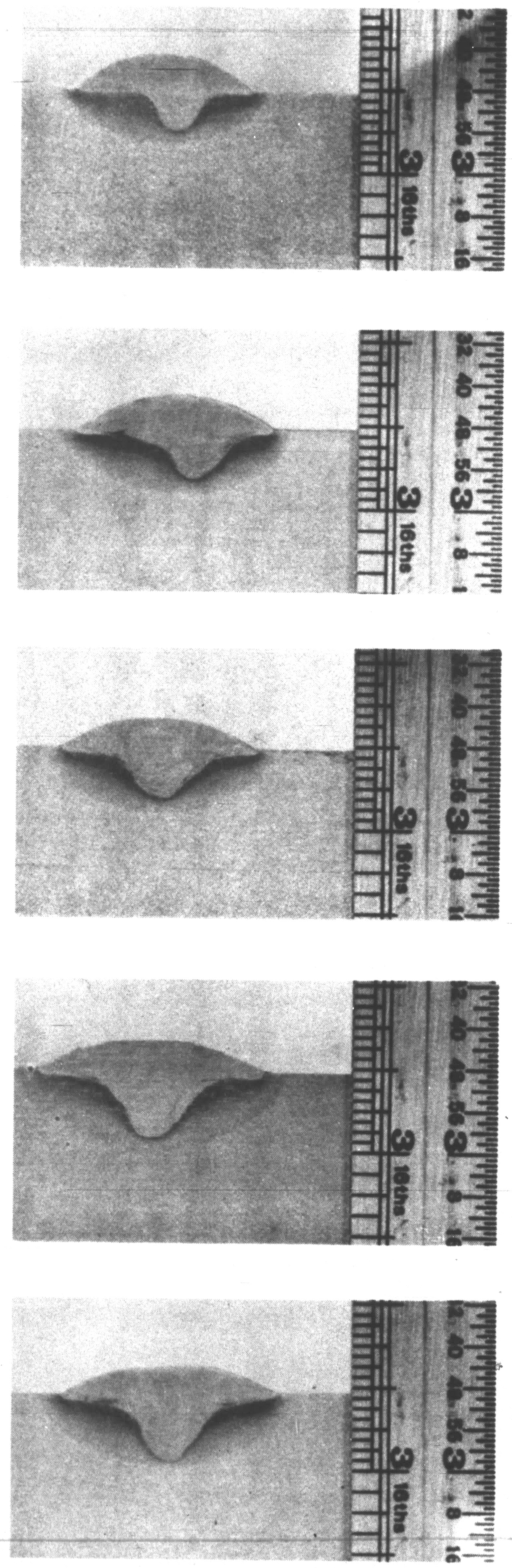


9 ATMOSPHERES ABSOLUTE



9 ATMOSPHERES ABSOLUTE

FIGURE 12. WELD CROSS-SECTIONS, 5/16 INCH (7.9mm) ARC, 5 PRESSURES



1 ATMOSPHERE ABSOLUTE

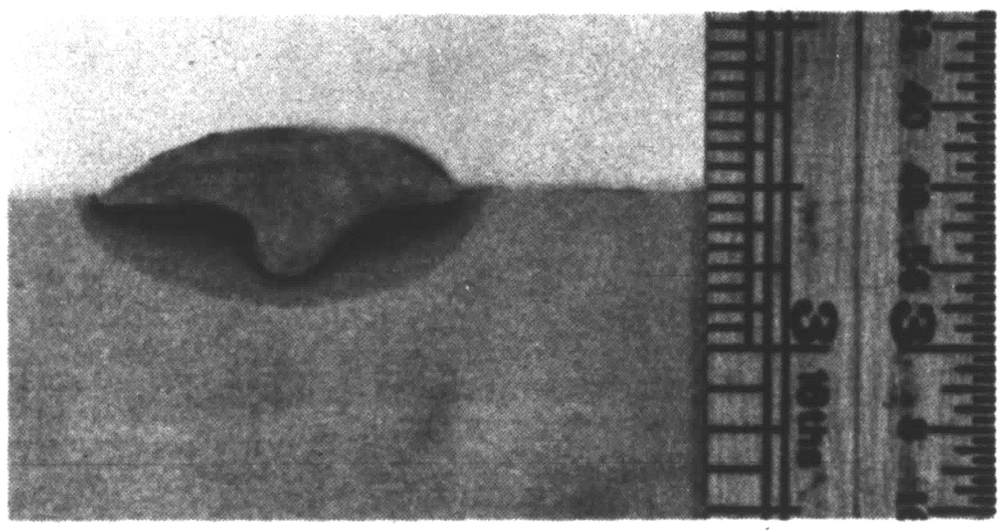
2 ATMOSPHERES ABSOLUTE

3 ATMOSPHERES ABSOLUTE

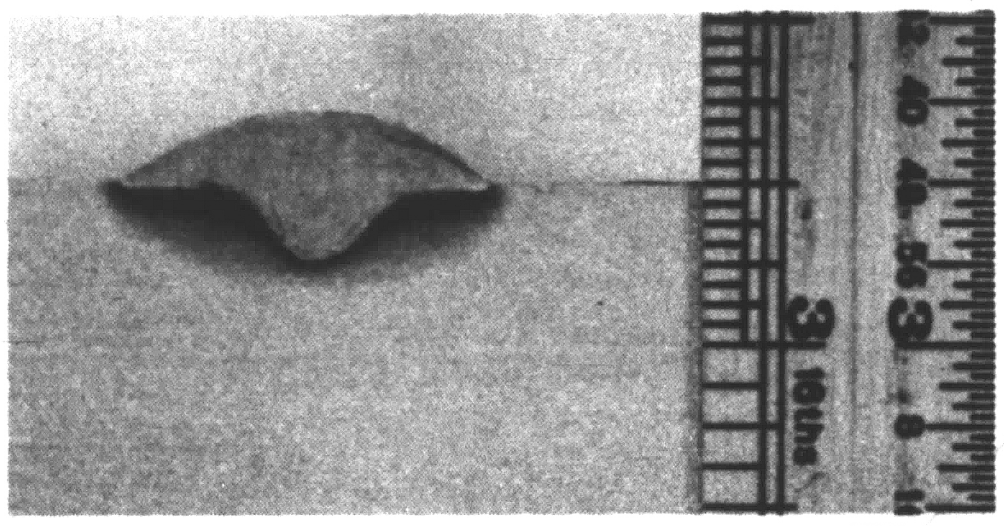
5 ATMOSPHERES ABSOLUTE

9 ATMOSPHERES ABSOLUTE

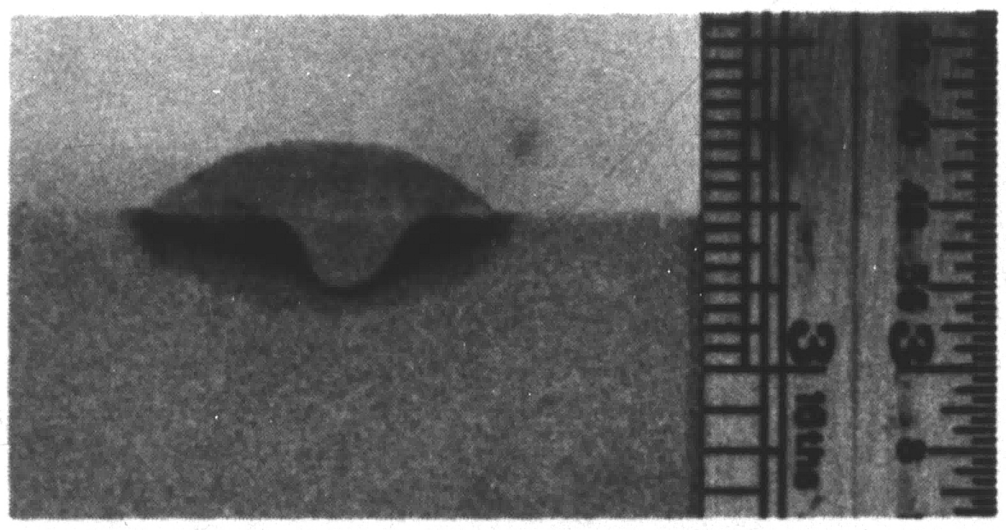
FIGURE 13. WELD CROSS-SECTIONS, 1 ATMOSPHERE ABSOLUTE, 3 ARC LENGTHS



3/16 INCH (4.8mm) ARC

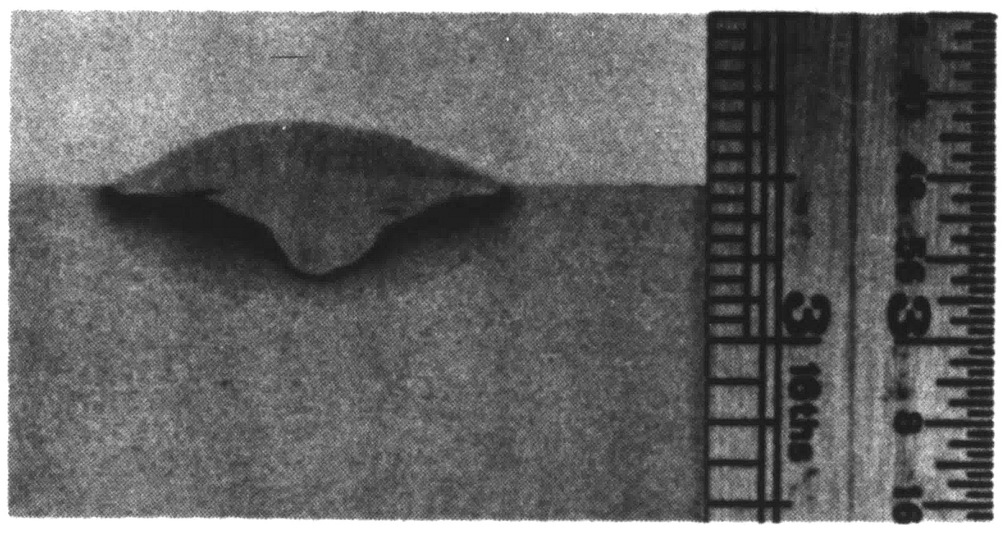


4/16 INCH (6.4mm) ARC

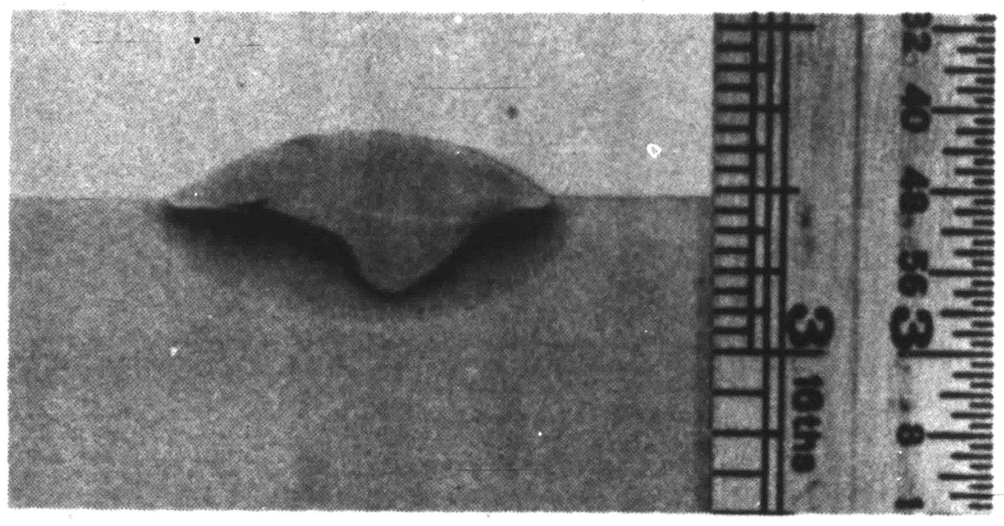


5/16 INCH (7.9mm) ARC

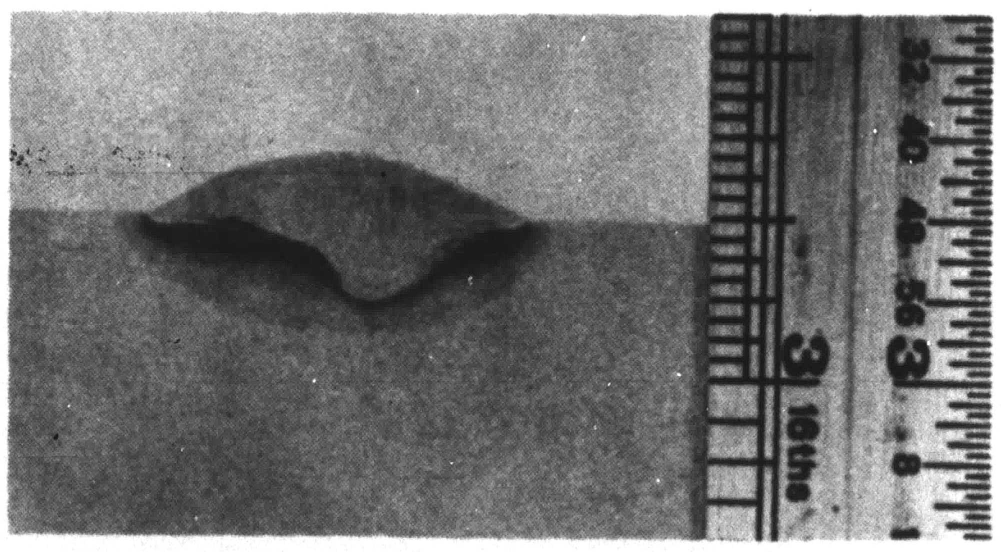
FIGURE 14. WELD CROSS-SECTIONS, 2 ATMOSPHERES ABSOLUTE, 3 ARC LENGTHS



3/16 INCH (4.8mm) ARC

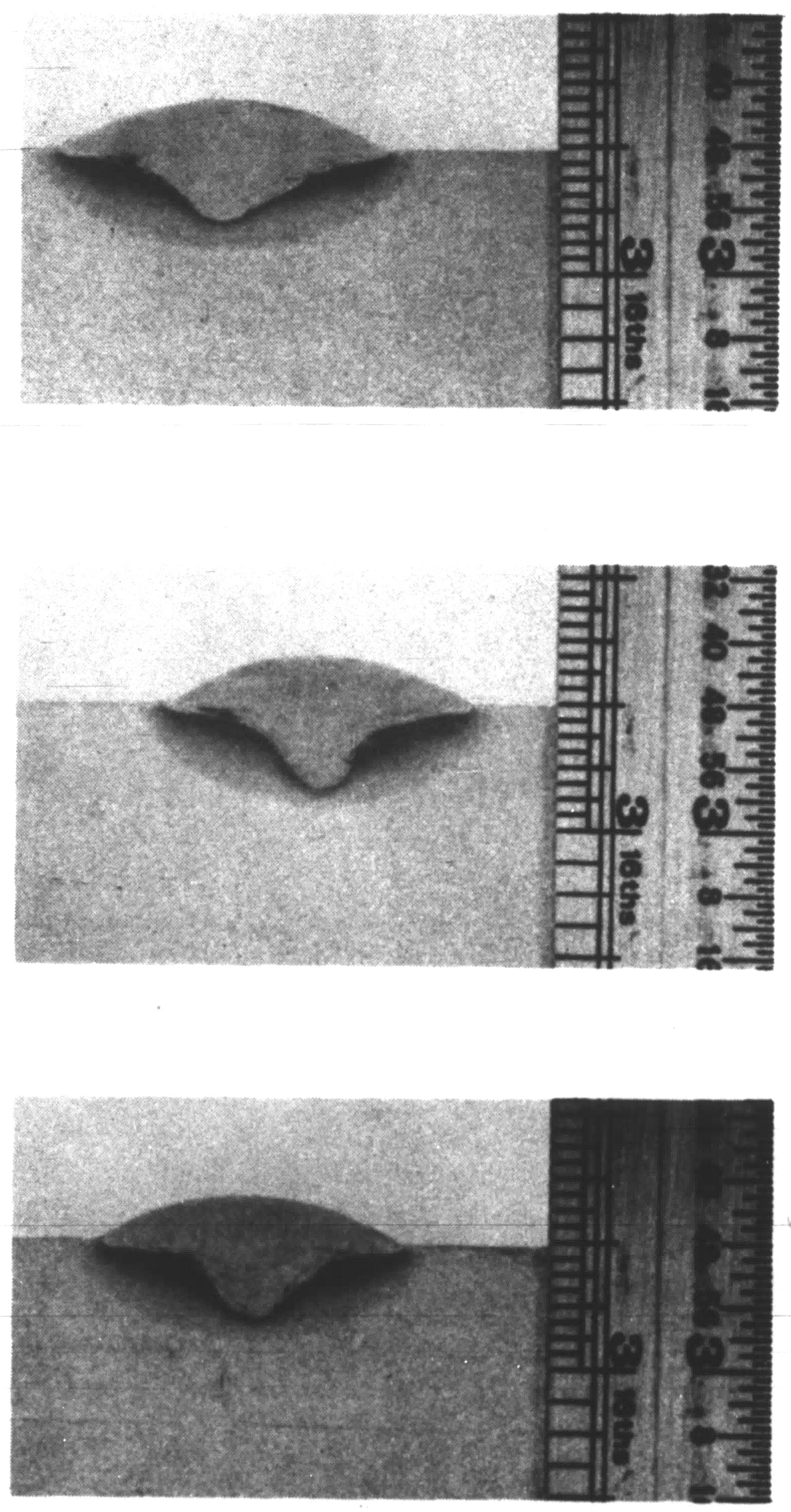


4/16 INCH (6.4mm) ARC



5/16 INCH (7.9mm) ARC

FIGURE 15. WELD CROSS-SECTIONS, 3 ATMOSPHERES ABSOLUTE, 3 ARC LENGTHS

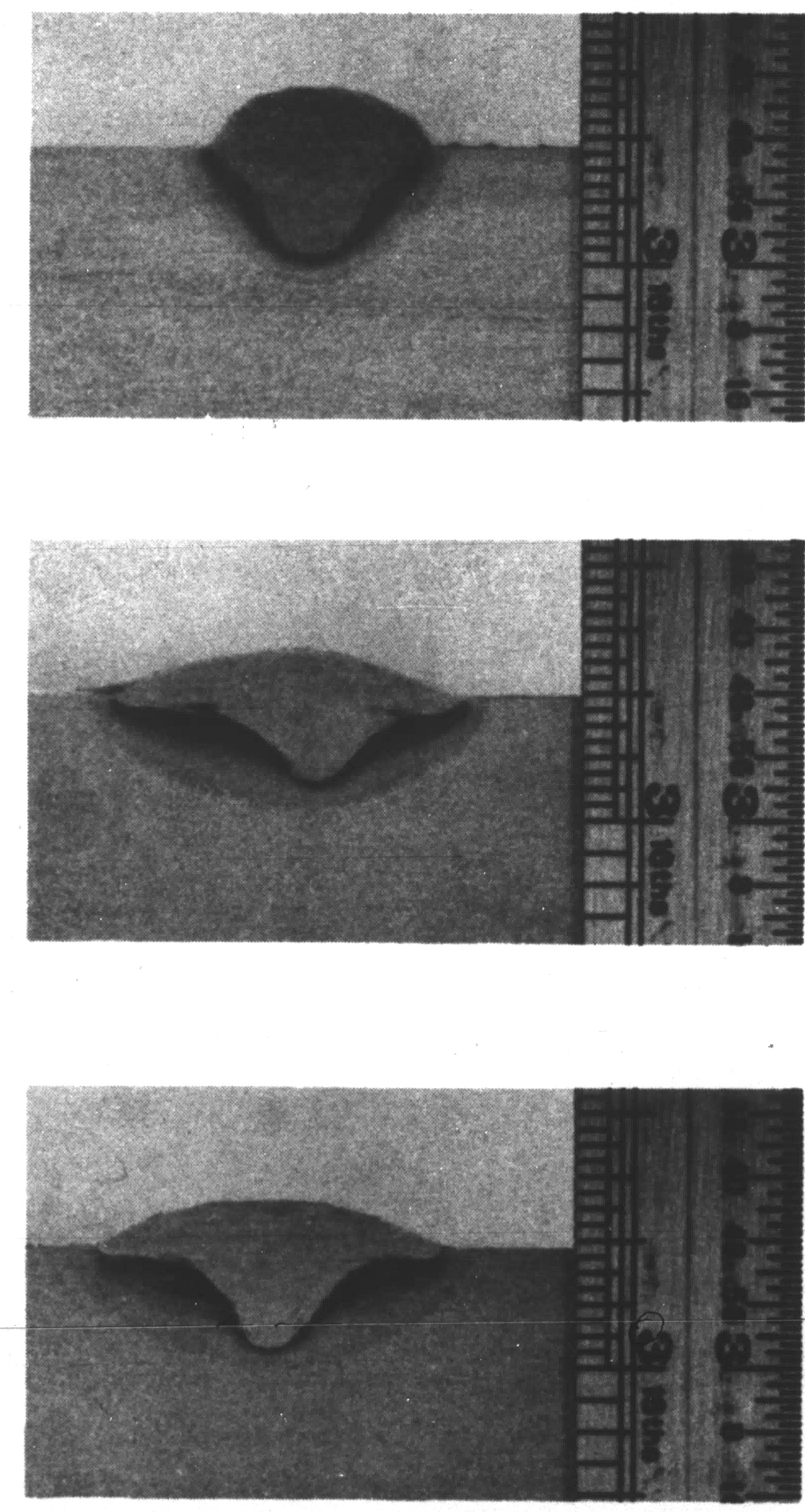


3/16 INCH (4.8mm) ARC

4/16 INCH (6.4mm) ARC

5/16 INCH (7.9mm) ARC

FIGURE 16. WELD CROSS-SECTIONS, 5 ATMOSPHERES ABSOLUTE, 3 ARC LENGTHS

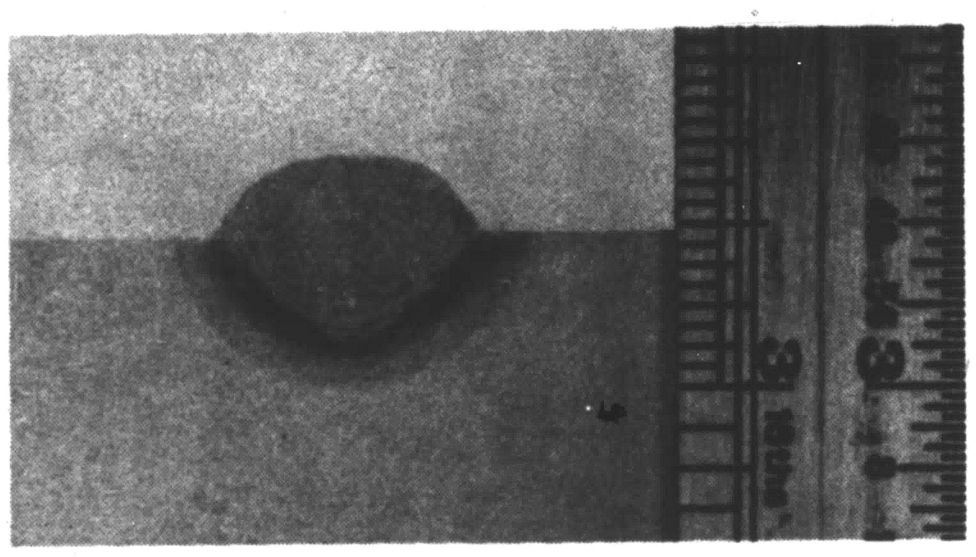


3/16 INCH (4.8mm) ARC

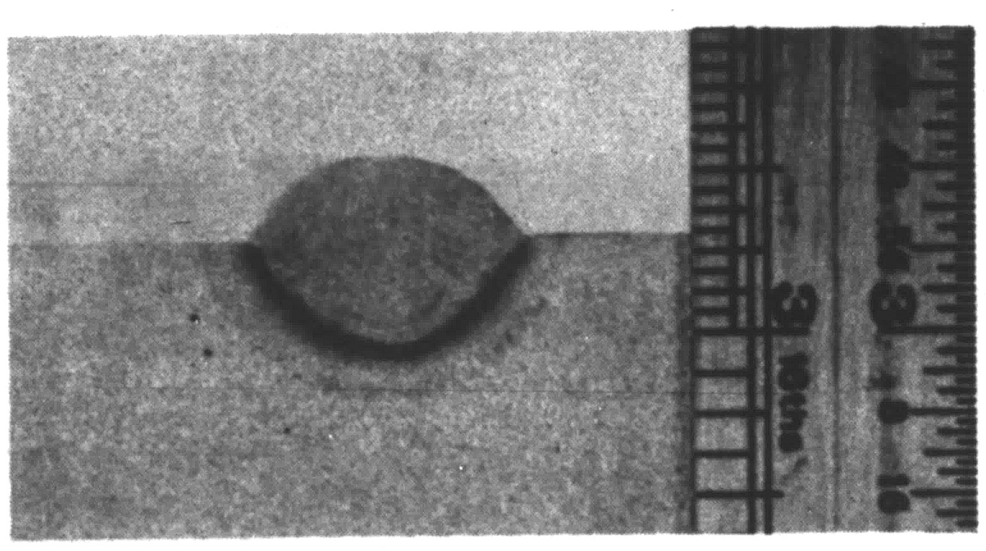
4/16 INCH (6.4mm) ARC

5/16 INCH (7.9mm) ARC

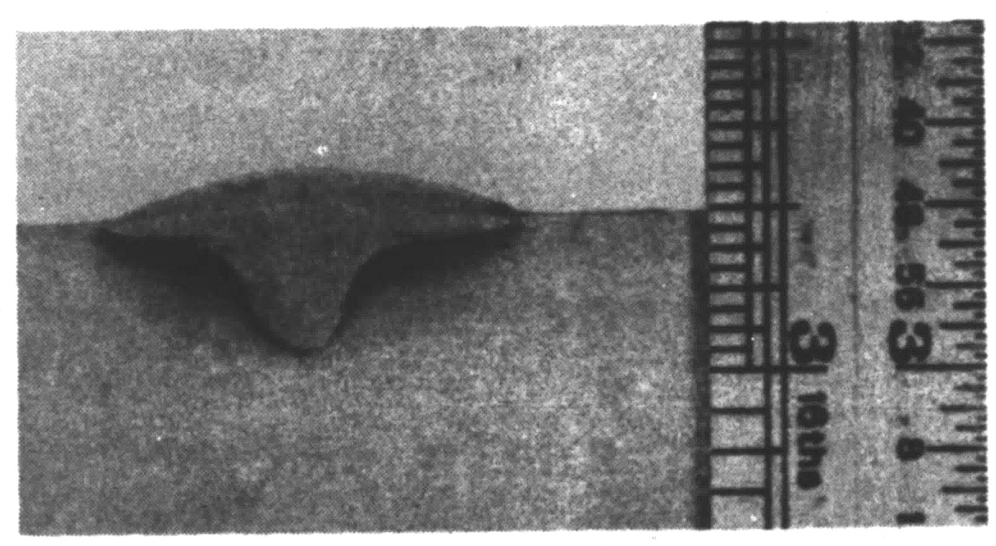
FIGURE 17. WELD CROSS-SECTIONS, 9 ATMOSPHERES ABSOLUTE, 3 ARC LENGTHS



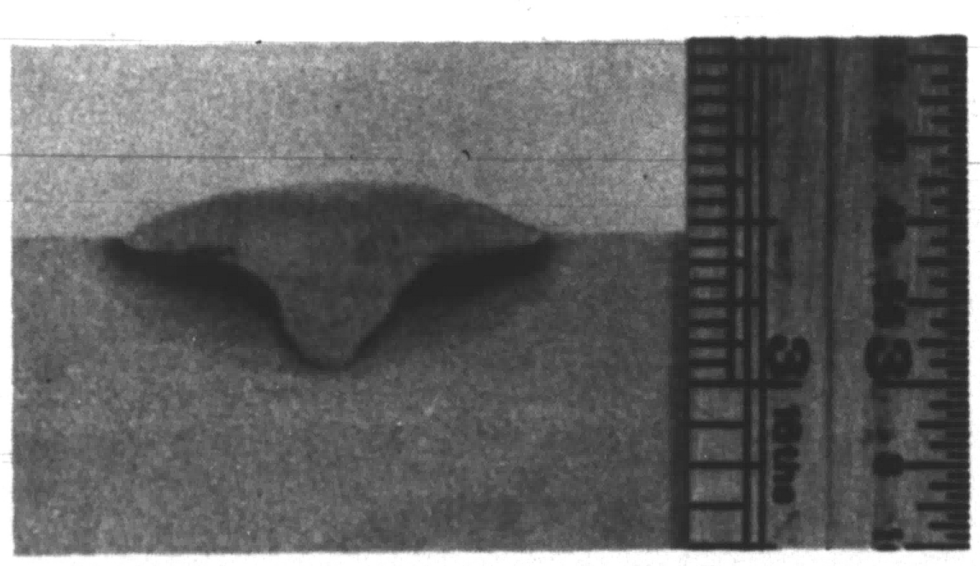
3/16 INCH (4.8mm) ARC



4/16 INCH (6.4mm) ARC



4/16 INCH (6.4mm) ARC



5/16 INCH (7.9mm) ARC

TABLE 1

COMPOSITION OF BASE AND FILLER METAL

	C	Mn	P	S	Si
Electrode Wire*	.11	1.10	.010	.028	.51
Base Metal**	.25	.67	.008	.019	.23

* Airco A675

** A212B

TABLE 2

TRANSITION CURRENTS AND VOLTAGES AT VARYING AMBIENT PRESSURES

(0.045" electrode, 1/4" arc, 1/2" stickout)
(1.2mm electrode, 6.4 mm arc, 12.7 mm stickout)

Pressure (atm abs)	Current (amp)	Voltage (volt)	Wire Feed* (ipm)	(cm/sec)
1	200	27.5	220	(9.3)
2	215	32	250	(10.6)
3	220	35	230	(9.7)
5	230	40	260	(11.0)
9	232	44	240	(10.1)

*Travel speed constant at 8.9 ipm (0.377 cm/sec)

TABLE 3 - WELDING PARAMETERS

Arc Length in.	(mm)	Stickout in.	(mm)	Pressure atm abs	Current amp	Voltage volt	Surface	Width in.	(mm)	Depth* in.	(mm)	Cross-Section in^2	(mm^2)
3/16	(4.8)	1/2	(12.7)	1	250	28	Flat	.578	(14.7)	.132	(3.35)	.066	(42.6)
3/16	(4.8)	1/2	(12.7)	2	260	32	Flat	.638	(16.2)	.140	(3.56)	.075	(48.4)
3/16	(4.8)	1/2	(12.7)	3	264	36	Flat	.671	(17.0)	.156	(3.96)	.085	(54.9)
3/16	(4.8)	1/2	(12.7)	5	262	38	Crowned	.453	(11.5)	.210	(5.33)	.095	(61.3)
3/16	(4.8)	1/2	(12.7)	9	262	39	Crowned	.453	(11.5)	.171	(4.34)	.082	(52.9)
1/4	(6.4)	1/2	(12.7)	1	246	28.5	Flat	.593	(15.1)	.125	(3.18)	.068	(43.8)
1/4	(6.4)	1/2	(12.7)	2	256	33.5	Flat	.625	(15.9)	.156	(3.96)	.072	(46.4)
1/4	(6.4)	1/2	(12.7)	3	258	37	Flat	.625	(15.9)	.171	(4.34)	.085	(54.9)
1/4	(6.4)	1/2	(12.7)	5	262	42	Flat	.703	(17.9)	.171	(4.34)	.097	(62.6)
1/4	(6.4)	1/2	(12.7)	9	268	44	Flat	.664	(16.9)	.203	(5.15)	.087	(56.1)
1/4	(6.4)	1/2	(12.7)	9	264	44	Crowned	.445	(11.3)	.164	(4.16)	.091	(58.7)
5/16	(7.9)	1/2	(12.7)	1	240	29	Flat	.562	(14.3)	.132	(3.35)	.069	(44.5)
5/16	(7.9)	1/2	(12.7)	2	256	35	Flat	.609	(15.5)	.140	(3.56)	.076	(49.0)
5/16	(7.9)	1/2	(12.7)	3	260	38	Flat	.625	(15.9)	.148	(3.76)	.081	(52.2)
5/16	(7.9)	1/2	(12.7)	5	260	43	Flat	.718	(18.2)	.210	(5.33)	.097	(62.6)
5/16	(7.9)	1/2	(12.7)	9	264	46.5	Flat	.687	(17.5)	.210	(5.33)	.095	(61.3)

*Measured normal to original plate surface

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